

CHAPTER 9

CULVERTS

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9.1 INTRODUCTION

9.1.1 Definition

A culvert is defined as the following:

- A structure that is usually designed hydraulically to take advantage of ponding at the inlet to increase hydraulic capacity.
- A structure used to convey surface runoff and/or irrigation water through embankments.
- A structure, as distinguished from bridges, that is usually covered by road embankment.

Following is a list of advantages and disadvantages of culverts:

Advantages

- Almost always will stop headcutting.
- Can be extended.
- Minimize structure scour hazards.
- Facilitate stage construction, eliminating the need for detours.
- Generally requires less maintenance than bridges.
- Can provide additional cover for fish where riparian buffer is lacking.
- Prevents de-icing salts to deposit directly into streams.

Disadvantages

- Can block fish passage.
- Can create scour hole at outlet
- Excessive headwater can cause flooding nuisance.

9.1.2 Purpose

This Chapter provides design procedures for the hydraulic design of highway culverts that are based on FHWA Hydraulic Design Series No. 5 (HDS 5), *Hydraulic Design of Highway Culverts* (Reference (8)). This Chapter also:

- presents results of culvert analysis using microcomputers that emphasizes the use of the HYDRAIN system (Reference (7)) and the HY8 culvert analysis software (Reference (6)), and
- provides a summary of the design philosophy contained in the *AASHTO Highway Drainage Guidelines*, Chapter 4 (Reference (1)).

9.1.3 Concepts

Following are discussions of concepts that are important in culvert design:

Critical Depth

In channels with regular cross section, critical depth is the depth at which the specific energy of a given flow rate is at a minimum. For a given discharge and cross-section geometry, there is only one critical depth. HDS 5 contains critical depth charts for different shapes.

Crown

The crown is the inside top of the culvert.

Flow Line

The flow line is the lowest elevation in a channel. The pipe invert can be above or below the flow line of a channel.

Free Outlet

A free outlet has a tailwater equal to or lower than critical depth. For culverts having free outlets, lowering of the tailwater has no effect on the discharge or the backwater profile upstream of the tailwater.

Improved Inlet

An improved inlet has an entrance geometry that decreases the flow contraction at the inlet and thus increases the capacity of culverts. These inlets are referred to as either side- or slope-tapered (walls or increased flow-line slope at the entrance).

Inlet Control

Inlet control occurs when the culvert barrel is capable of conveying more flow than the **inlet lets through**.

Invert

The invert is the flow-line of the culvert (inside bottom).

Normal Flow

Normal flow occurs in a channel reach when the discharge, velocity and depth of flow do not change throughout the reach. The water surface and channel bottom will be parallel. This type of flow will exist in a culvert operating on a constant slope provided that the culvert is sufficiently long.

Outlet Control

Outlet control occurs when the culvert barrel is not capable of conveying as much flow as the inlet can accept.

Slope

- Steep slope - where critical depth is greater than normal depth.
- Mild slope - where critical depth is less than normal depth.

Submerged

A submerged outlet occurs where the tailwater elevation is higher than the crown of the culvert.

A submerged inlet occurs where the headwater is greater than $1.2D$, where D is the culvert diameter or barrel height.

9.1.4 Symbols

To provide consistency within this Chapter and throughout this *Manual*, the symbols given in Table 9-1 will be used. These symbols were selected because of their wide use in culvert publications.

9.2 POLICY

9.2.1 Definition

Policy is a set of goals that establish a definite course of action or method of action and that are selected to guide and determine present and future decisions (see Policy Chapter). Policy is implemented through design criteria for making decisions (see Section 9.3).

9.2.1.1 Culvert Location, Termini and Appurtenances

Culverts should be located so as to match the natural channel in line and grade, maintaining the existing flow regime. In unusual cases where this is not practicable, as when right-of-way is not a factor:

- a. Evaluate changes to stream storage functions and increased erosion to downstream banks
 - b. Incorporate mitigation elements and strategies into the design. Extend irrigation culverts from right-of-way line to right-of-way line. Exceptions require written approval of the Region Director.
- In new construction (or reconstruction) of drainage structures, outlet velocities should not be unduly increased beyond the UDOT right-of-way. Investigate aesthetically pleasing energy dissipation strategies for culverts in sensitive and scenic areas. Coordinate with UDOT's landscape designer without compromising essential hydraulic parameters.
 - Consider the appropriate use of trash racks, debris deflectors, vertical pipe risers and debris basins on all drainage or irrigation crossings where a large amount of debris is expected. Experience has shown that trash racks in these applications need to be installed at slopes of 3:1 or flatter to maintain efficiency.
 - Use sag pipes, or inverted siphons only where no other solution is practical. All sag pipe or inverted siphon designs must include a detailed silting hazard evaluation, winter draining provisions, and maintenance cost analysis approved by the Region Maintenance Engineer.
 - Directly incorporate applicable elements of the latest UDOT Standards for erosion and sediment control into culvert designs.

9.2.1.2 Culvert Size and Materials Requirements

The minimum diameter of pipe for drainage or irrigation crossings is:

1. 24 in on interstate highways
2. 24 in on primary highways
3. 18 in on secondary highways.

The minimum diameter for under-drains is 12-inches. Provide cleanout boxes for maintenance at intervals of 200 ft to 300 ft. To maintain self-cleaning velocity, the minimum grade for underdrains should be 0.003 ft/ft where feasible. In case of a depressed section of highway intercepting the water table, periodically drain underdrains into a storm drain. Place the underdrains so that the hydraulic grade line of the storm drain does not reverse the flow into the underdrains causing the subgrade to become saturated.

Approved types of Culverts are:

1. Reinforced concrete:
 - a. pre-cast
 - b. cast-in-place
2. Non-reinforced concrete:
 - a. pre-cast
 - b. cast-in-place
3. Corrugated steel:
 - a. with bolted joints
 - b. with welded joints
 - c. Helical steel with crimped joints
4. Corrugated aluminum:
 - a. with riveted joints
 - b. with bolted joints
 - c. Helical aluminum with crimped joints
5. Pre-cast Clay
6. High Density Polyethylene (HDPE)
 - a. Corrugated
 - b. Smooth lined
7. Smooth-lined Polyvinyl Chloride (PVC)

- B. The material used for underdrains can be aluminum, steel, concrete, PVC, clay, or HDPE.

9.2.1.3 Headwalls and End-Sections

When feasible, use prefabricated flared end sections rather than headwalls to maintain embankment geometry and provide advantages of economy, traffic safety enhancement, and aesthetics. Where right-of-way is limited, headwalls and associated wingwalls may be necessary to provide hydraulic efficiency and stability, and to retain embankment materials.

The following list summarizes Departmental policy concerning culverts, headwalls, end sections and other related items:

- A. Materials, methods and workmanship shall be in accordance with the latest edition of UDOT's Standard Specifications.
- B. Use headwalls or end sections, as appropriate.
 - 1. Headwalls are required on all:
 - a. Circular culverts larger than 48-in
 - b. Arches larger than 60-in x 35-in.
 - 2. Headwalls or end sections are required on all culverts located on:
 - a. Interstate highways
 - b. Primary highways
 - 3. Required on culverts located on:
 - a. Secondary highways:
Only when analysis shows exposed culvert end elements are subject to significant uplift forces or similar detrimental hydraulic loadings during high flow events, or when skewed crossings using flexible culverts lack the stiffness to support the unbalanced embankment loads imposed.
 - 4. Use end sections:
 - a. In urban and urbanizing areas where the ends of a projecting culvert will be visible from adjacent roads or developed property.
 - 5. End sections may be used:
 - a. In special use areas or view areas if recommended by the landscape designer.
 - b. To marginally improve the hydraulic capacity of a culvert.
 - c. As part of an anchorage system to improve resistance to uplift loadings.
 - 6. Do not use end sections or headwalls on irrigation culverts unless hydraulically required.

TABLE 9-1 — Symbols and Definitions

Symbol	Definition	Units
A	Area of cross section of flow	ft ²
AHW	Allowable HW	ft
B	Barrel width	in or ft
D	Culvert diameter or barrel height	in or ft
d	Depth of flow	ft
d _c	Critical depth of flow	ft
g	Acceleration due to gravity	ft/s ²
H	Sum of H _E + H _f + H _o	ft
H _b	Bend headloss	ft
H _E	Entrance headloss	ft
H _f	Friction headloss	ft
H _L	Total energy losses	ft
H _o	Outlet or exit headloss	ft
H _v	Velocity head	ft
h _o	Hydraulic grade line height above outlet invert	ft
HW	Headwater depth (subscript indicates section)	ft
k _E	Entrance loss coefficient	-
L	Length of culvert	ft
N	Manning's roughness coefficient	-
P	Wetted perimeter	ft
Q	Rate of discharge	ft ³ /s
R	Hydraulic radius (A/P)	ft
S	Slope of culvert	ft/ft
TW	Tailwater depth above invert of culvert	ft
V	Mean velocity of flow with barrel full	ft/s
V _d	Mean velocity in downstream channel	ft/s
V _o	Mean velocity of flow at culvert outlet	ft/s
V _u	Mean velocity in upstream channel	ft/s
γ	Unit weight	lb/ft ³
τ	Tractive force	lb/ft ²

9.2.2 Drainage Culverts

The following policies are specific to culverts:

- All culverts shall be hydraulically designed.
- The overtopping flood selected shall be consistent with the class of highway and commensurate with the risk at the site.
- Culvert location in both plan and profile shall be investigated to minimize the potential for sediment buildup in culvert barrels.

- The cost savings of multiple use (utilities, stock and wildlife passage, land access and fish passage) shall be weighed against the advantages of separate facilities.
- Culverts shall be designed to accommodate debris or proper provisions shall be made for debris maintenance.
- Material selection shall include consideration of service life that includes abrasion and corrosion.
- Culverts shall be located and designed to present a minimum hazard to traffic and people.
- The detail of documentation for each culvert site shall be commensurate with the risk and importance of the structure. Design data and calculations shall be assembled in an orderly fashion and retained for future reference as provided for in the Documentation Chapter.
- Where practicable, some means shall be provided for personnel and equipment access to facilitate maintenance.
- Culverts shall be regularly inspected and maintained.

9.2.3 Irrigation Culverts

- All irrigation culverts larger than 1.5-feet in diameter shall be hydraulically designed.
- All irrigation culverts shall have water tight joints.
- All irrigation culverts shall be aligned vertically and horizontally with the canal, to avoid or minimize sediment buildup.
- Culvert material selection shall address pipe abrasion.
- Culverts shall be designed and located to minimize hazard to traffic and pedestrians. All pipe culverts 36-inch in diameter and smaller shall be extended to the right-of-way line. Pipe culverts larger than 36-inch in diameter need not to extend to the right-of-way line upon written release of the Region Director.
- Access shall be provided for maintenance personnel and equipment to irrigation culverts that do not extend to the right-of-way line.
- The detail of documentation for each culvert site shall be commensurate with the risk and importance of the structure. Design data and calculations shall be assembled in an orderly fashion and retained for future reference as provided for in the Documentation Chapter.

9.3 DESIGN CRITERIA

9.3.1 Definition

Design criteria are the standards by which a policy is implemented or placed into action. They form the basis for the selection of the final design configuration. Listed below by categories are the design criteria that shall be considered for all culvert designs.

9.3.2 Site Criteria

9.3.2.1 Structure Type Selection

Culverts are used:

- where bridges are not hydraulically required,
- where debris and ice are tolerable, and
- where more economical than a bridge.

Bridges are used:

- where culverts cannot be used,
- where more economical than a culvert,
- to satisfy land-use requirements,
- to mitigate environmental harm caused by a culvert,
- to avoid floodway or irrigation canal encroachments, and
- to accommodate ice and large debris.

9.3.2.2 Length and Slope

The culvert length and slope shall be chosen to approximate existing topography, and to the degree practicable:

- the culvert invert shall be aligned with the channel bottom and the skew angle of the stream, and
- the culvert entrance shall match the geometry of the roadway embankment.

9.3.2.3 Floating Ice

Floating ice shall be mitigated as necessary by:

- increasing the culvert height 1 ft above the total of the maximum observed ice level, and
- increasing the culvert width to encompass the channel and
- by fully anchoring the culvert in an appropriate headwall.

9.3.2.4 Debris Control

Debris control shall be designed using HEC 9 (4) and shall be considered:

- where experience or physical evidence indicates the watercourse will transport a heavy volume of controllable debris,
- for culverts located in mountainous or steep regions,
- for culverts that are under high fills, and

- where clean-out access is limited. However, access must be available to clean out the debris-control device.

9.3.3 Design Limitations

9.3.3.1 Allowable Headwater

Allowable headwater is the depth of water that can be ponded at the upstream end of the culvert during the design flood, which will be limited by one or more of the following:

- non-damaging to upstream property,
- below the edge of the shoulder,
- a maximum of 0.5-foot increase over the existing 100-year flood elevation in FEMA mapped floodplain,
- a maximum of 1-foot increase over the 100-year flood elevation in unmapped floodplains.
- equal to the elevation where flow diverts around the culvert.

9.3.3.2 Tailwater Relationship (Channel)

- Evaluate the hydraulic conditions of the downstream channel to determine a tailwater depth for a range of discharges, which includes the review discharge (see Channel Chapter).
- Use a single cross-section analysis.
- Calculate backwater curves at sensitive locations.
- Use the average of the critical depth and the pipe diameter if the culvert outlet is operating with a free outfall.
- Use the headwater elevation of any nearby, downstream culvert, or control structure, if it is greater than the channel depth.

9.3.3.3 Tailwater Relationship (Confluence or Large-Water Body)

- Use the high-water elevation that has the same frequency as the design flood if events are known to occur concurrently (statistically dependent).
- If statistically independent, evaluate the joint probability of flood magnitudes, and use a likely combination resulting in the greater tailwater depth. An example is provided in Table 13-7, Joint Probability Analysis.

9.3.3.4 Maximum Velocity

The maximum velocity at the culvert exit shall be consistent with the velocity in the natural channel or shall be mitigated with:

- channel stabilization (see Channel Chapter), and
- energy dissipation (see Energy Dissipator Chapter).

9.3.3.5 Minimum Velocity

The minimum velocity in the culvert barrel shall result in a tractive force ($\tau = \gamma dS$) greater than critical τ of the transported streambed material at low-flow rates.

- Use 2.5 ft/s when streambed material size is not known.
- If clogging is probable, consider installation of a sediment trap or a size of culvert to facilitate cleaning.

9.3.3.6 Storage (Temporary or Permanent)

If storage is being assumed upstream of the culvert, consideration shall be given to:

- the total area of flooding,
- recommending that the storage area will remain available for the life of the culvert through the purchase of right-of-way or easement, in areas of possible development.

9.3.3.7 Flood Frequency

The flood frequency used to design or review the culvert shall be based on:

- According to the roadway classification – see Table 3.1 in the Policy chapter and Table A1 of the Hydrology chapter;
- the level of risk associated with failure of the crossing, increasing backwater or redirection of the floodwaters;
- location of FEMA-mapped floodplains.

9.3.4 Design Features

9.3.4.1 Culvert Sizes and Shape

The culvert size and shape selected shall be based on engineering and economic criteria related to site conditions:

- The following minimum sizes shall be used to avoid maintenance problems and clogging:
 - 24 in for Interstate System,
 - 18 in for other systems.
- Land-use requirements (e.g., need for a cattle pass) can dictate a larger or different barrel geometry than required for hydraulic considerations.
- Use arch or oval shapes only if required by hydraulic limitations, minimum cover requirements, site conditions.
- Open bottom arches shall be used only after a detailed scour analysis is completed.

9.3.4.2 Broken-Back Culverts

A broken-back culvert, which combines two different slopes, may be necessary to accommodate a large differential of flow line elevation or may result from one or more extensions to an original straight profile culvert. See Appendix 9.F for a procedure on the hydraulic design of a broken-back culvert.

9.3.4.3 Multiple Barrels

Multiple-barrel culverts shall fit within the natural dominant channel with minor widening of the channel to avoid conveyance loss through sediment deposition in some of the barrels. The designer will evaluate installation of a berm around the inlets of the additional pipes. Where existing channel contains a well defined low flow channel, at least one pipe shall be placed in the low-flow channel with the additional pipes placed at the bank-full elevation. They are to be avoided where:

- the approach flow is high velocity, particularly if supercritical. (These sites require either a single barrel or special inlet treatment to avoid adverse hydraulic jump effects.);
- irrigation canals or ditches are present unless approved by the canal or ditch owner;
- fish passage is required unless special treatment is provided to ensure adequate low flows (commonly one barrel is lowered);
- a high potential exists for debris problems (clogging of culvert inlet); or
- a meander bend is present immediately upstream.

9.3.4.4 Material Selection

The material selection shall be according to UDOT's Culvert Service Life Guidelines. Figure 9.1 shows the pipe material selection flowchart.

The material selected shall be based on a comparison of the total cost of alternative materials over the design life of the structure, which is dependent upon the following:

- bed load,
 - structural strength,
 - hydraulic roughness,
 - bedding/foundation conditions,
 - abrasion and corrosion resistance, and
 - water-tightness requirements.
- The selection shall not be made using first cost as the only criteria.

9.3.4.5 Culvert Skew

The culvert skew shall not exceed 35° as measured from a line perpendicular to the roadway centerline without the approval of the Region Hydraulic Engineer.

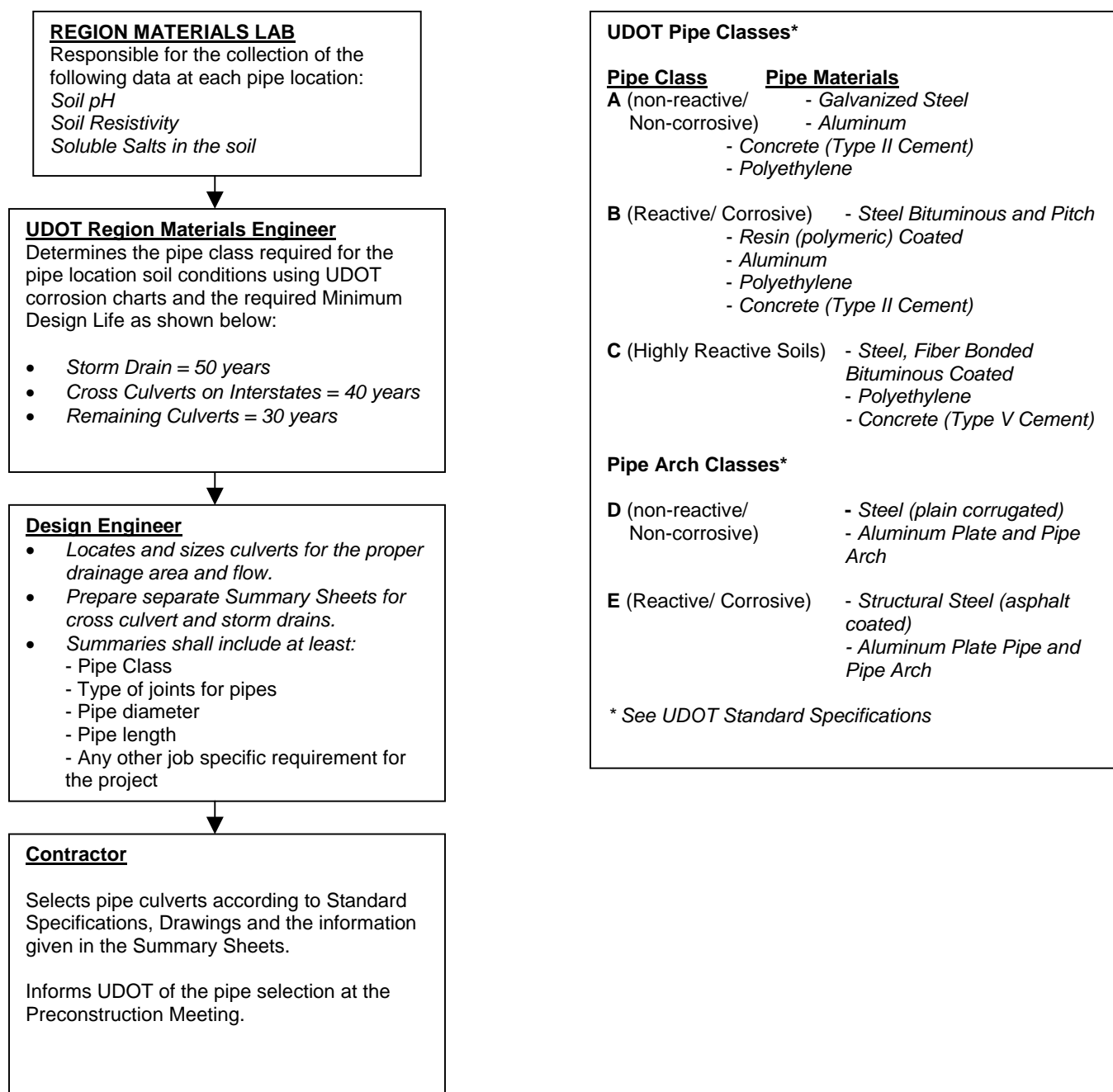


FIGURE 9-1 — UDOT Pipe Selection Flow Chart

9.3.4.6 End Treatment (Inlet or Outlet)

The culvert inlet type shall be selected from the following list based on the considerations given and the inlet coefficient, k_E . (A table of recommended values of k_E is included in Appendix 9.E). Consideration shall also be given to safety, because some end treatments can be hazardous to

errant vehicles. All culverts 48 in in diameter and larger should have headwalls or slope paving on the inlet end.

9.3.4.6.1 Projecting Inlets or Outlets

- Extend 2-feet beyond the roadway embankment for 1:2 and steeper slopes are susceptible to damage during roadway maintenance and from errant vehicles.
- Have low construction cost.
- Have poor hydraulic efficiency for thin materials.
- Flexible culverts shall include anchoring the inlet to strengthen the leading edge and prevent uplift for culverts 36 in diameter and larger.

9.3.4.6.2 Mitered Inlets

- Are hydraulically more efficient than thin-edge projecting.
- shall be mitered to match the fill slope.
- shall include anchoring the inlet to strengthen the weak, leading edge for culverts 36 in diameter and larger.

9.3.4.6.3 Headwalls with Bevels

- Increase the efficiency of metal pipe.
- Provide embankment stability and embankment erosion protection.
- Provide protection from buoyancy.
- Shorten the required structure length.
- Reduce maintenance damage.

Consideration shall be given to the use of step bevel ends for round metal pipes larger than 48 inch in diameter.

9.3.4.6.4 Improved Inlets

- shall be considered for culverts that will operate in inlet control.
- Can increase the hydraulic performance of the culvert, but may also add to the total culvert cost. Therefore, they should only be used if practicable.
- With a slope-taper, shall not be considered where fish passage is required.

9.3.4.6.5 Commercial Metal End Sections

- Are available for corrugated metal, concrete and thermoplastic pipe.
- Retard embankment erosion and incur less damage from maintenance.
- May improve projecting metal-pipe entrances by increasing hydraulic efficiency, reducing the accident hazard and improving their appearance.

- Are hydraulically equal to a headwall, but can be equal to a beveled or side-tapered entrance if a flared, enclosed transition occurs before the barrel.
- Shall be used for flexible pipes up to 48 in and maybe used with rigid pipes up to 84 in diameter.

9.3.4.6.6 Wingwalls

- Are used to retain the roadway embankment to avoid a projecting culvert barrel.
- Are used where the side slopes of the channel are unstable.
- Are used where the culvert is skewed to the normal channel flow.
- Can be used to transition from a wide channel to narrower culverts.
- Provide the best hydraulic efficiency if the flare angle is between 30° and 60°.

9.3.4.6.7 Aprons

- Are used to reduce scour from high headwater depths or from approach velocity in the channel.
- shall extend at least one pipe diameter upstream.
- shall not protrude above the normal streambed elevation. Place apron at a slope from the invert of the pipe to the flowline of the channel.

9.3.4.6.8 Cut-off Walls

- Are used to prevent piping along the culvert barrel and undermining at the culvert ends.
- shall be used on all culverts with headwalls or slope paving.
- shall be a minimum of 1.5 ft depth.

9.3.4.7 **Safety Considerations**

Traffic shall be protected from culvert ends as follows:

- Small culverts (30 in in diameter or less) shall use an end section or slope paving.
- Culverts greater than 30 in in diameter shall receive one of the following:
 - a. Be extended to the appropriate “clear zone” distance per Reference (2).
 - b. Shielded with a traffic barrier if the culvert is very large, cannot be extended, has a channel that cannot be safely traversed by a vehicle, or has a significant flooding hazard with a grate.
- Periodically inspect each site to determine if safety problems exist for traffic or for the structural safety of the culvert and embankment.

9.3.4.8 **Weep Holes**

If weep holes are used to relieve uplift pressure, they shall be designed similar to underdrain systems.

9.3.4.9 Performance Curves

Performance curves, or tables shall be developed for all culverts for evaluating the hydraulic capacity of a culvert for various headwaters, outlet velocities and scour depths. These curves will display the consequence of high-flow rates at the site and provide a basis for evaluating flood hazards. For culverts larger than 36 in diameter, analyze one size larger and one size smaller than the recommended size.

9.3.5 Related Designs

9.3.5.1 Buoyancy Protection

Headwalls, endwalls, slope paving or other means of anchoring to provide buoyancy protection shall be considered for all flexible culverts. Buoyancy is more serious with steepness of the culvert slope, depth of the potential headwater (debris blockage may increase), flatness of the upstream fill slope, height of the fill, large culvert skews or mitered ends.

9.3.5.2 Outlet Protection (See Energy Dissipator Chapter)

In general, scour holes at culvert outlets provide efficient energy dissipators. As such, outlet protection for the selected culvert design flood shall only be provided where the outlet scour hole depth computations indicate:

- the scour hole will undermine the culvert outlet,
- the expected scour hole may cause costly property damage,
- the scour hole causes a nuisance effect (most common in urban areas),
- the scour hole blocks fish passage, or
- the scour hole will restrict land-use requirements.

9.3.5.3 Relief Opening

Where multiple-use culverts or culverts serving as relief openings have their outlet set above the normal stream flow line, special precautions shall be required to prevent headcuts or erosion from undermining the culvert outlet.

9.3.5.4 Land-Use Culverts

Consideration shall be given to combining drainage culverts with other land-use requirements necessitating passage under a highway:

- during the selected design flood, the land use is temporarily forfeited but available during lesser floods;
- two or more barrels are required with one situated to be dry during floods less than the selected design flood;
- the outlet of the higher land-use barrel may need protection from headcutting;
- shall be sized to ensure it can serve its intended land frequency use function up to and including a 2-yr flood; and

- the height and width constraints shall satisfy the hydraulic or land-use requirements, whichever is larger.

9.3.5.5 Erosion and Sediment Control

Temporary measures shall be included in the construction plans. These measures include the use of the following: silt boxes, straw silt barriers, brush silt barriers, filter cloth, temporary silt fence and check dams. For more information, see the Erosion and Sediment Control Chapter.

9.3.5.6 Environmental Considerations and Fishery Protection

Care must be exercised in selecting the location of the culvert site to controlling erosion, sedimentation and debris. Select a site that will permit the culvert to be constructed and will limit the impact on the stream or wetlands. For more information, see the Surface Water Environment Chapter.

9.3.5.7 Irrigation Facilities

Unless legally abandoned, an irrigation structure shall be required even if the irrigation canal or ditch is no longer used. The canal or ditch owner shall approve the use of multiple-barrel culverts. Provision shall be made to accommodate any water escaping the ditch to avoid a flood hazard. Irrigation facilities shall be designed to accommodate the water and flood right using the criteria below which yields the largest culvert size:

- constrain the headwater within the existing canal or ditch banks unless provision is made for overflow during high flows,
- provide freeboard to pass expected debris,
- no increase in the velocity beyond what the unprotected ditch material or protection will sustain,
- avoid a flood hazard from a canal or ditch failure,
- provide a width capable of delivering the water and flood right at its existing operating depth, and
- provide for known winter ice accumulation problems.

Design flows for existing irrigation crossings are listed in order of preference. The following data is required for existing facility crossing modification:

- Data from the canal company.
- Capacity of the existing system based on a water surface profile.
- Water-rights data from the Utah Department of Water Resources.

For design of new crossings, the existing crossing should be modeled using a standard step backwater model such as HEC-RAS. The model can be calibrated by documenting the water surface and the flow at the time of the survey,

Irrigation facilities will be designed to accommodate flood water surcharges using the criteria outlined below:

- Contain flow within the existing canal banks.
- Provide freeboard to accommodate normal debris.
- Maximum backwater of 4 inches subject to approval of the ditch owner.
- No increase in velocity beyond existing.

9.4 DESIGN PHILOSOPHY

9.4.1 Overview

The design of a culvert system for a highway crossing of a floodplain involves using information from the following Chapters in this *Manual* (Policy, Documentation, Planning and Location, Hydrology, Channels, Energy Dissipators, Storm Drainage Systems, Surface Water Environment and Erosion and Sediment Control). Each of these should be consulted as appropriate. The discussion in this Section is focused on alternative analysis and design methods.

9.4.2 Alternative Analysis

Culvert alternatives shall be selected that satisfy:

- topography, and
- design policies and criteria.

Alternatives shall be analyzed for:

- environmental impact,
- hydraulic equivalency, and
- risk and cost.

Select an alternative that best integrates engineering, economic and political considerations. The chosen culvert shall meet the selected structural and hydraulic criteria and shall be based on:

- construction and maintenance costs,
- risk of failure or property damage,
- traffic safety,
- environmental or aesthetic considerations,
- political or nuisance considerations, and
- land-use requirements.

9.4.3 Design Methods

The designer shall choose whether:

- to use a culvert, storm drain or inverted siphon;
- to assume a constant discharge or route a hydrograph; or
- to use nomographs or computer software.

9.4.3.1 Structure Type

Culvert

- Is a covered structure with both ends open.
- Designed using procedures of HDS 5 (8).

Storm Drain (See Storm Drainage System Chapter)

- Is a covered structure with either end in a manhole and is usually a part of a system of pipes.
- Explained in HEC 22 (11).
- Designed using HYDRA software contained in HYDRAIN.

Inverted Siphon (See Appendix 9.B)

- Is a covered structure that is sometimes termed a sag culvert with both ends open and operates at a low head. The invert profile dips below the approach and exit channels.
- Designed using procedures in Reference (13).

9.4.3.2 Design Discharge Approach

Constant Discharge

- Is assumed for most culvert designs.
- Is usually the peak discharge.
- Will yield a conservatively sized structure where temporary storage is available but not used.

Hydrograph and Routing

- Storage capacity behind a highway embankment attenuates a flood hydrograph and reduces the peak discharge.
- Significant storage will reduce the required culvert size.
- Is checked by routing the design hydrographs through the culvert site to determine the outflow hydrograph and stage (backwater) behind the culvert.
- Procedures are in Section 9.9 and HDS 5, Section V (8).

9.4.3.3 Computational Methods (Nomographs)

- Require a trial-and-error solution, which is quite easy and provides reliable designs for many applications.

- Require additional computations for tailwater, outlet velocity, hydrographs, routing and roadway overtopping.
- Circular and box shapes are included at the end of this Chapter. Other shapes and improved inlets are found in HDS 5.
- Electronic version of the nomographs are at <http://www.fhwa.dot.gov/bridge/hydsoft.htm> as HDS 5 Chart Calculator.

9.4.3.4 Computer Software

HYDRAIN is a microcomputer system which:

- Is recommended by AASHTO.
- Includes HY8.
- Has a fully documented users manual.

HY8 (FHWA Culvert Analysis Software):

- Is an interactive program written in Basic.
- Uses the theoretical basis for the nomographs.
- Can compute tailwater, improved inlets, roadway overtopping, hydrographs, routing and multiple independent barrels.
- Develops and plots tailwater rating curves.
- Develops and plots performance curves.
- Is documented in *HYDRAIN Users Manual (7)*.

CDS (Wyoming Culvert Design System) (14)

- Is a batch operation program written in Fortran.
- Includes roadway overtopping capability.
- Plots performance curves for headwater, outlet velocity and outlet scour.
- Includes options for both design and analysis.
- Computes tailwater for any cross section shape with up to 10 subsections.
- Has extensive flood-routing capability.
- Is documented in the *Users Manual* for HYDRAIN (7).

The CDS is available from:

Hydraulics Section
Wyoming Highway Department
Cheyenne, WY 82009

9.5 DESIGN EQUATIONS

9.5.1 General

An exact theoretical analysis of culvert flow is extremely complex because the following is required:

- analyzing nonuniform flow with regions of both gradually varying and rapidly varying flow;
- determining how the flow type changes as the flow rate and tailwater elevations change;
- applying backwater and drawdown calculations, energy and momentum balance;
- applying the results of hydraulic model studies; and
- determining if hydraulic jumps occur and if they are inside or downstream of the culvert barrel.

9.5.2 Approach

The procedures in this Chapter use the following.

9.5.2.1 Control Section

The control section is the location where there is a unique relationship between the flow rate and the upstream water surface elevation.

Inlet control is governed by the inlet geometry.

Outlet control is governed by a combination of the culvert inlet geometry, the barrel characteristics and the tailwater or critical depth.

9.5.2.2 Minimum Performance

Minimum performance is assumed by analyzing both inlet and outlet control and using the highest headwater. The culvert may operate more efficiently at times (more flow for a given headwater level), but it will not operate at a lower level of performance than calculated.

9.5.3 Inlet Control

For inlet control, the control section is at the upstream end of the barrel (the inlet). The flow passes through critical depth near the inlet and becomes shallow, high-velocity (supercritical) flow in the culvert barrel. Depending on the tailwater, a hydraulic jump may occur downstream of the inlet.

9.5.3.1 Headwater Factors

Headwater depth is measured from the inlet invert of the inlet control section to the surface of the upstream pool.

Inlet area is the cross-sectional area of the face of the culvert. Generally, the inlet face area is the same as the barrel area.

Inlet edge configuration describes the entrance type. Some typical inlet edge configurations are thin-edge projecting, mitered, square edges in a headwall and beveled edge.

Inlet shape is usually the same as the shape of the culvert barrel. Typical shapes are rectangular, circular, elliptical and arch. Check for an additional control section, if different than the barrel.

9.5.3.2 Hydraulics

Three regions of flow are shown in the Figure 9-2: unsubmerged, transition and submerged.

9.5.3.3 Unsubmerged

For headwater between the invert and the culvert height, the entrance operates as a weir:

- A weir is a flow control section where the upstream water surface elevation can be predicted for a given flow rate.
- The relationship between flow and water surface elevation must be determined by model tests of the weir geometry or by measuring prototype discharges.
- These tests are then used to develop equations. Appendix A of HDS 5 (8) contains the equations that were developed from model test data; see Figure 9-3, Flow Type I.

9.5.3.4 Submerged

For headwaters above the inlet, the culvert operates as an orifice:

- An orifice is an opening, submerged on the upstream side and flowing freely on the downstream side, which functions as a control section.
- The relationship between flow and headwater can be defined based on results from model tests. Appendix A of HDS 5 (8) contains flow equations which were developed from model test data. See Figure 9-4, Flow Type V.

9.5.3.5 Transition Zone

The transition zone is located between the unsubmerged and the submerged flow conditions where the flow is poorly defined. This zone is approximated by plotting the unsubmerged and submerged flow equations and connecting them with a line tangent to both curves.

9.5.3.6 Nomographs

The inlet control flow versus headwater curves which are established using the above procedure are the basis for constructing the inlet control design nomographs. Note that, in the inlet control nomographs, HW is measured to the total upstream energy grade line including the approach velocity head.

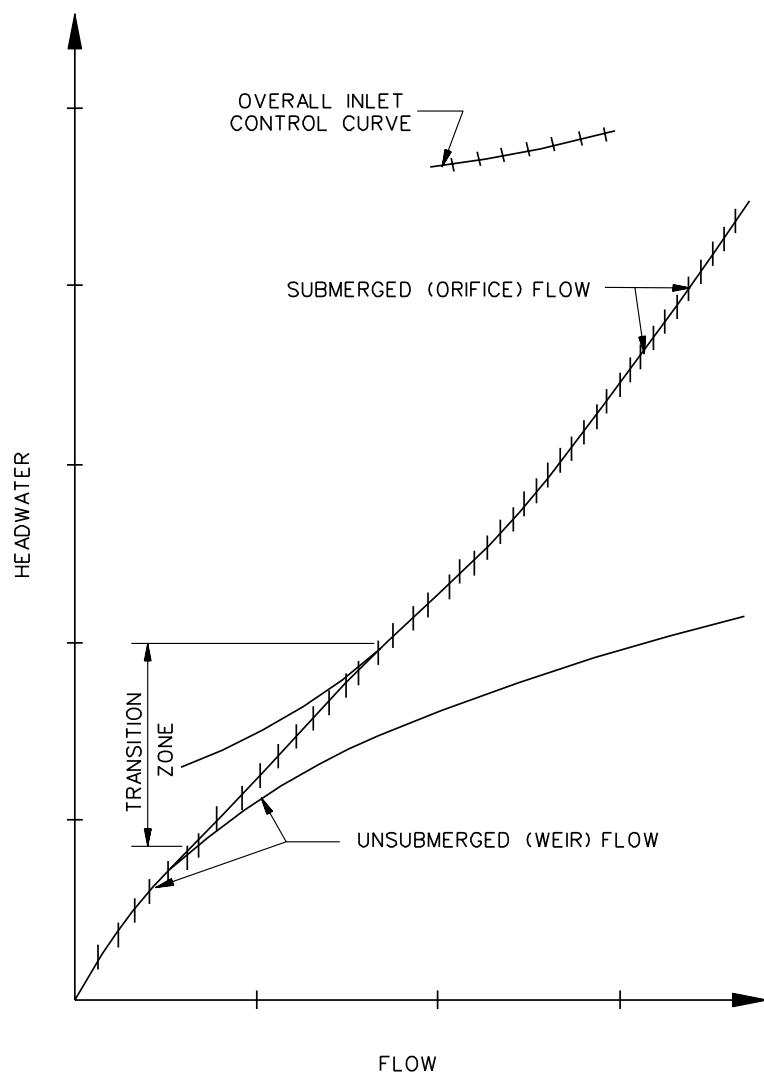


FIGURE 9-2 — Unsubmerged, Transition and Submerged

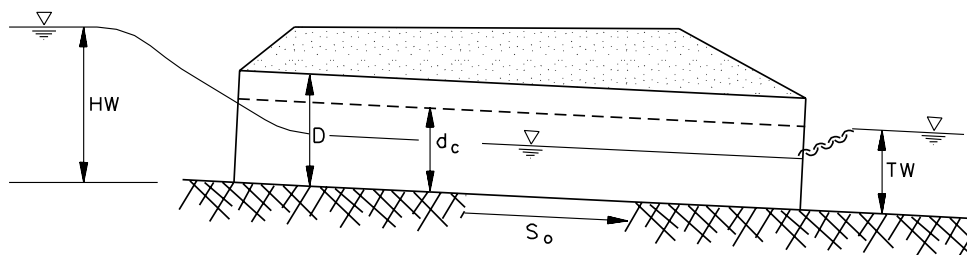


FIGURE 9-3 — Flow Type I

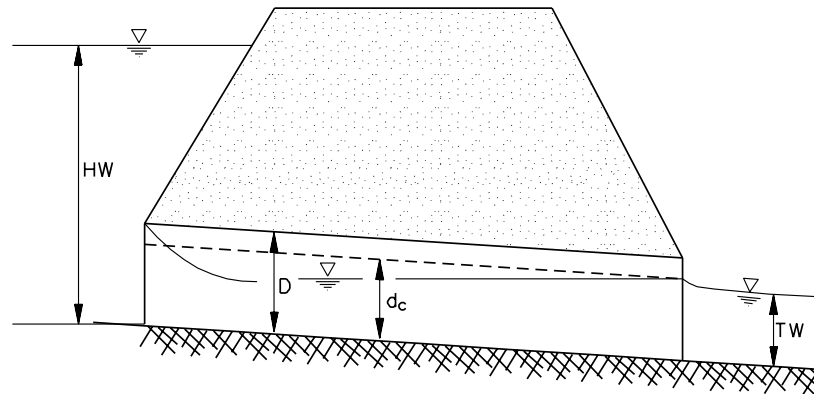


FIGURE 9-4 — Flow Type V

9.5.4 Outlet Control

Outlet control has depths and velocity that are subcritical. The control of the flow is at the downstream end of the culvert (the outlet). The tailwater depth is either assumed to be critical depth near the culvert outlet or the downstream channel depth, whichever is higher. In a given culvert, the type of flow is dependent on all of the barrel factors. All of the inlet control factors also influence culverts in outlet control.

9.5.4.1 Barrel Roughness

Barrel roughness is a function of the material used to fabricate the barrel. Typical materials include concrete and corrugated metal. The roughness is represented by a hydraulic resistance coefficient; i.e., the Manning n value. Typical Manning n values are presented in Appendix 9.E.

9.5.4.2 Barrel Area

Barrel area is measured perpendicular to the flow.

9.5.4.3 Barrel Length

Barrel length is the total culvert length from the entrance crown to the exit crown of the culvert. Because the design height of the barrel and the slope influence the actual length, an approximation of barrel length is usually necessary to begin the design process.

9.5.4.4 Barrel Slope

Barrel slope is the actual slope of the culvert barrel and is often the same as the natural stream slope. However, where the culvert inlet or outlet is raised or lowered, the barrel slope is different from the stream slope.

9.5.4.5 Tailwater Elevation

Tailwater is based on the downstream water surface elevation. Backwater calculations from a downstream control, a normal depth approximation, or field observations are used to define the tailwater elevation (see Section 9.3.3).

9.5.4.6 Hydraulics

Full flow in the culvert barrel is assumed for the analysis of outlet control hydraulics. Outlet control flow conditions can be calculated based on an energy balance from the tailwater pool to the headwater pool. Outlet control can occur as full, partial flow or a combination of both through the culvert:

1. Losses: $H_L = H_E + H_f + H_v + H_b + H_j + H_g$ (9.1)

where:

- H_L = total energy loss, ft
- H_E = entrance loss, ft
- H_f = friction losses, ft
- H_v = exit loss (velocity head), ft (equivalent to H_o ; see Equation 9.4d)
- H_b = bend losses, ft (see HDS 5 (8))
- H_j = losses at junctions, ft (see HDS 5)
- H_g = losses at grates, ft (see HDS 5)

2. Velocity: $V = Q/A$ (9.2)

where:

- V = average barrel velocity, ft/s
- Q = flow rate, ft³/s
- A = cross sectional area of flow with the barrel full, ft²

3. Velocity head: $H_v = V^2/2g$ (9.3)

where:

- g = acceleration due to gravity, 32.2 ft/s²

4. Entrance loss: $H_E = k_E (V^2/2g)$ (9.4a)

where:

- k_E = entrance loss coefficient; see Table 9.E-2 in Appendix 9.E

5. Friction loss: $H_f = [(29n^2L)/R^{1.33}] [V^2/2g]$ (9.4b)

where:

- n = Manning's roughness coefficient (see Table 9.E-1 in Appendix 9.E)
- L = length of the culvert barrel, ft
- R = hydraulic radius of the full culvert barrel = A/P , ft
- P = wetted perimeter of the barrel, ft

6. Exit loss: $H_o = 1.0 [(V^2/2g) - (V_d^2/2g)]$ (9.4c)

where:

- V_d = channel velocity downstream of the culvert, ft/s (usually neglected; see Equation 9.4d).

$$H_o = H_v = V^2/2g \quad (9.4d)$$

7. Barrel losses: $H = H_E + H_o + H_f$

$$H = [1 + k_e + (19.63n^2L/R^{1.33})] [V^2/2g] \quad (9.5)$$

9.5.4.7 Energy Grade Line

The energy grade line represents the total energy at any point along the culvert barrel. Equating the total energy at Sections 1 and 2, upstream and downstream of the culvert barrel in Figure 9-5, the following relationship results:

$$HW_o + (V_u^2/2g) = TW + (V_d^2/2g) + H_L \quad (9.6)$$

where: HW_o = headwater depth above the outlet invert, ft
 V_u = approach velocity, ft/s
 TW = tailwater depth above the outlet invert, ft
 V_d = downstream velocity, ft/s
 H_L = sum of all losses (Equation 9.1)

Note that this Equation is only true if TW is higher than critical depth at the outlet.

9.5.4.8 Hydraulic Grade Line

The hydraulic grade line is the depth to which water would rise in vertical tubes connected to the sides of the culvert barrel. In full flow, the energy grade line and the hydraulic grade line are parallel lines separated by the velocity head except at the inlet and the outlet.

9.5.4.9 Nomographs (Full Flow)

The nomographs were developed assuming that the culvert barrel is flowing full and:

- $TW \geq D$, Flow Type IV (see Figure 9-5); or
- $d_c \geq D$, Flow Type VI (see Figure 9-6)

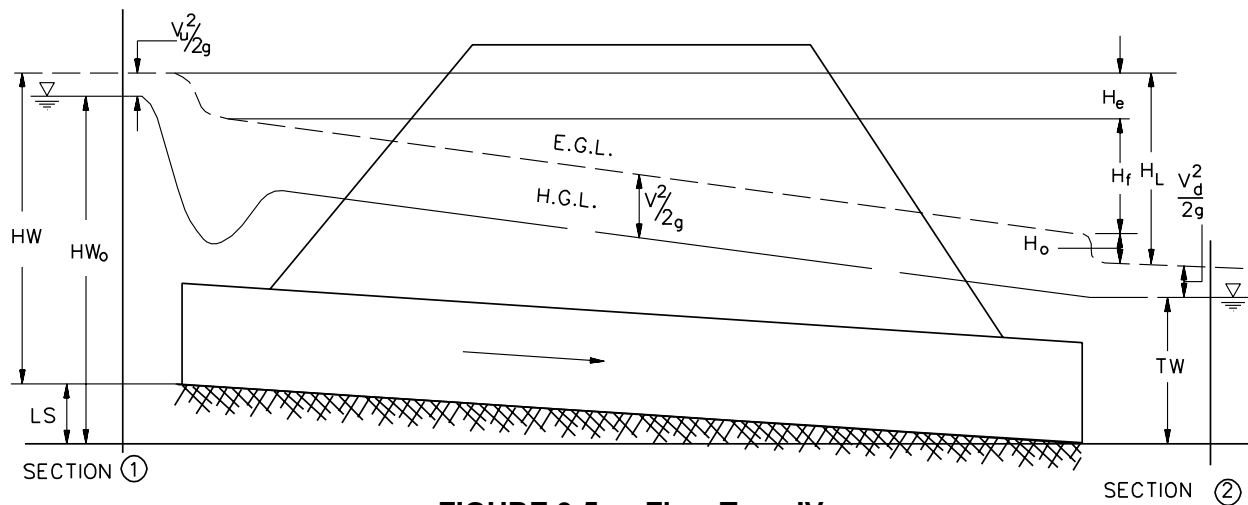


FIGURE 9-5 — Flow Type IV

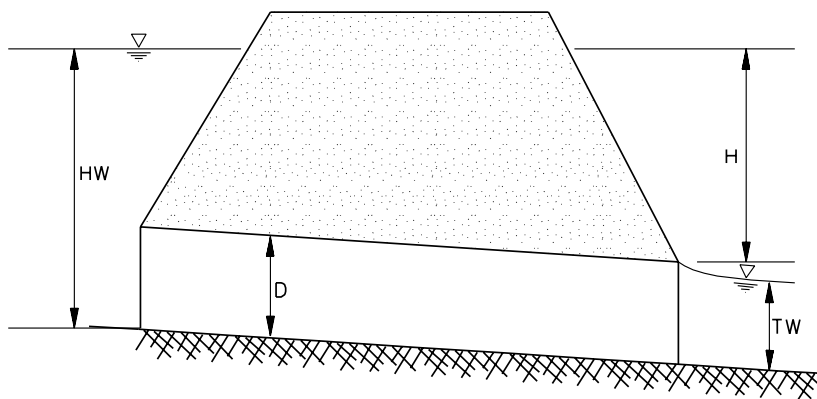


FIGURE 9-6 — Flow Type VI

- V_u is small and its velocity head can be considered to be a part of the available headwater (HW) used to convey the flow through the culvert.
- V_d is small and its velocity head can be neglected.
- Equation (9.6) becomes:

$$HW = TW + H - S_oL \quad (9.7)$$

where: HW = depth from the inlet invert to the energy grade line, ft
 H = the value read from the nomographs (Equation 9.5), ft
 S_oL = drop from inlet to outlet invert, ft

9.5.4.10 Nomographs (Partial Full Flow)

Equations (9.1) through (9.7) were developed for full barrel flow. The Equations also apply to the flow situations which are effectively full-flow conditions, if $TW < d_c$; see Figure 9-7.

Backwater calculations may be required that begin at the downstream water surface and proceed upstream. If the depth intersects the top of the barrel, a full flow extends from that point upstream to the culvert entrance.

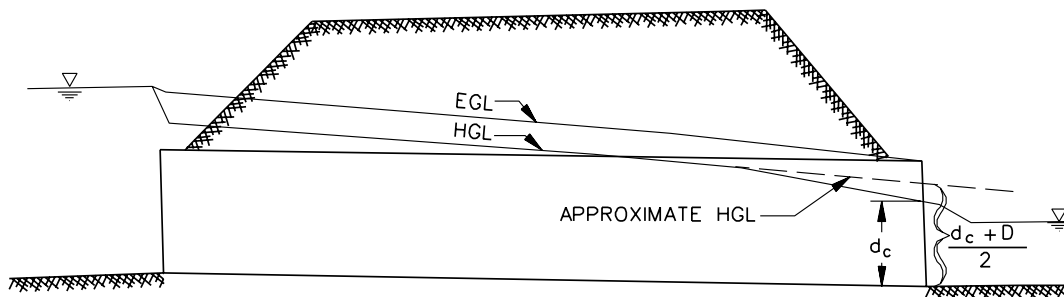


FIGURE 9-7 — Flow Type VII

9.5.4.11 Nomographs (Partial Full Flow) — Approximate Method

Based on numerous backwater calculations performed by the FHWA staff, it was found that the hydraulic grade line pierces the plane of the culvert outlet at a point approximately one-half of the way between critical depth and the top of the barrel, or $(d_c + D)/2$ above the outlet invert. The approximation should only be used if the barrel flows full for part of its length or the headwater is at least $0.75D$. If neither of these conditions are met, a water surface profile should be used to establish the hydraulic grade line. TW should be used if higher than $(d_c + D)/2$. The following equation should be used:

$$HW = h_o + H - S_o L \quad (9.8)$$

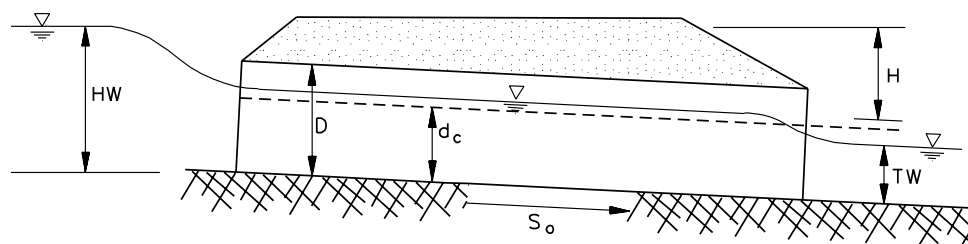
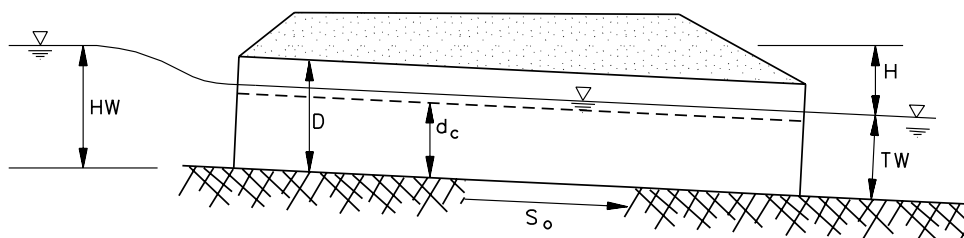
where: h_o = the larger of TW or $(d_c + D)/2$, ft

Adequate results are obtained down to a $HW = 0.75D$. For lower headwaters, backwater calculations are required.

(See Figure 9-9 if $TW < d_c$ and Figure 9-8 if $TW > d_c$)

9.5.5 Outlet Velocity

Culvert outlet velocities shall be calculated to determine the need for erosion protection at the culvert exit. Culverts usually result in outlet velocities that are higher than the natural stream velocities. These outlet velocities may require flow readjustment or energy dissipation to prevent downstream erosion. If outlet erosion protection is necessary, the flow depths and Froude number may also be needed (see Chapter 11, Energy Dissipators).

FIGURE 9-8 — Flow Type II, $TW < d_c$ FIGURE 9-9 — Flow Type III, $TW > d_c$

9.5.5.1 Inlet Control

The velocity is calculated from Equation 9.2 after determining the outlet depth. Either of the following methods may be used to determine the outlet depth:

- Calculate the water surface profile through the culvert. Begin the computation at d_c at the entrance and proceed downstream to the exit. Determine at the exit the depth and flow area.
- Assume normal depth and velocity. This approximation may be used because the water surface profile converges towards normal depth if the culvert is of adequate length. This outlet velocity may be slightly higher than the actual velocity at the outlet. Normal depths may be obtained from design aids in publications (e.g., HDS 3 (10), which is in US Customary units).

9.5.5.2 Outlet Control

The cross sectional area of the flow is defined by the geometry of the outlet and either critical depth, tailwater depth or the height of the conduit:

- Critical depth is used where the tailwater is less than critical depth.
- Tailwater depth is used where tailwater is greater than critical depth but below the top of the barrel.
- The total barrel area is used where the tailwater exceeds the top of the barrel.

9.5.6 Roadway Overtopping

Roadway overtopping will begin when the headwater rises to the elevation of the roadway. The overtopping will usually occur at the low point of a sag vertical curve on the roadway. The flow

will be similar to flow over a broad-crested weir. Flow coefficients for flow overtopping roadway embankments are found in HDS 1 (9) and in the documentation of HY-7 (5). Curves from the latter are included on Chart 60 in Appendix 9.D:

$$Q_r = C_d L HW_r^{1.5} \quad (9.9)$$

where: Q_r = overtopping flow rate, ft³/s
 C_d = overtopping discharge coefficient (weir coefficient) = $k_t C_r$
 k_t = submergence coefficient
 C_r = discharge coefficient
 L = length of the roadway crest, ft
 HW_r = the upstream depth, measured above the roadway crest, ft

9.5.6.1 Length

The length is difficult to determine where the crest is defined by a roadway sag vertical curve:

- Recommend subdividing into a series of segments. The flow over each segment is calculated for a given headwater. The flows for each segment are added together to determine the total flow.
- The length can be represented by a single horizontal line (one segment). The length of the weir is the horizontal length of this segment. The depth is the average depth (area/length) of the upstream pool above the roadway.

9.5.6.2 Total Flow

Total flow is calculated for a given upstream water surface elevation using Equation 9.9:

- Roadway overflow plus culvert flow must equal total design flow.
- A trial-and-error process is necessary to determine the flow passing through the culvert and the amount flowing across the roadway.
- Performance curves for the culvert and the road overflow may be summed to yield an overall performance.

9.5.7 Performance Curves

Performance curves are plots of flow rate versus headwater depth or elevation, velocity or outlet scour. The culvert performance curve consists of the controlling portions of the individual performance curves for each of the following control sections (see Figure 9-10):

Inlet

The inlet performance curve is developed using the inlet control nomographs (see Appendix 9.D).

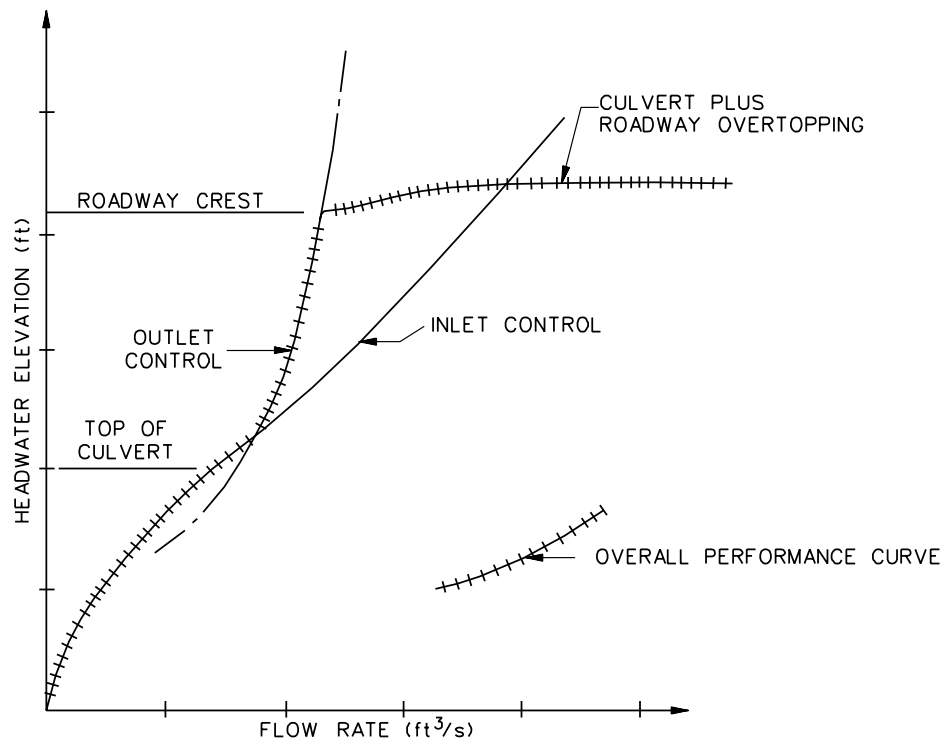


FIGURE 9-10 — Overall Performance Curve

Outlet

The outlet performance curve is developed using Equations 9.1 through 9.7, the outlet control nomographs (see Appendix 9.D), or backwater calculations.

Roadway

The roadway performance curve is developed using Equation 9.9.

Overall

The overall performance curve is the sum of the flow through the culvert and the flow across the roadway and can be determined by performing the following steps:

1. Select a range of flow rates and determine the corresponding headwater elevations for the culvert flow alone. These flow rates should fall above and below the design discharge and cover the entire flow range of interest. Both inlet and outlet control headwaters shall be calculated.
2. Combine the inlet and outlet control performance curves to define a single performance curve for the culvert.
3. When the culvert headwater elevations exceed the roadway crest elevation, overtopping will begin. Calculate the upstream water surface depth above the roadway for each selected flow rate. Use these water surface depths and Equation (9.9) to calculate flow rates across the roadway.

4. Add the culvert flow and the roadway overtopping flow at the corresponding headwater elevations to obtain the overall culvert performance curve as shown in Figure 9-10.

9.6 DESIGN PROCEDURE

The following design procedure provides a convenient and organized method for designing culverts for a constant discharge, considering inlet and outlet control. The procedure does not address the effect of storage, which is discussed in the Storage Chapter and Section 9.9.

- The designer should be familiar with all the equations in Section 9.5 before using these procedures.
- Following the design method without an understanding of culvert hydraulics can result in an inadequate, unsafe or costly structure.
- The computation form has been provided in Appendix 9.E to guide the user. It contains blocks for the project description, designer's identification, hydrologic data, culvert dimensions and elevations, trial culvert description, inlet and outlet control HW, culvert barrel selected and comments.

Step 1 Assemble Site Data And Project File

- a. See Data Chapter — The minimum data are:
 - USGS, site and location maps;
 - embankment cross section;
 - roadway profile;
 - photographs;
 - field visit (sediment, debris); and
 - design data at nearby structures.
- b. Studies by other agencies including:
 - small dams — NRCS, USACE, TVA, BLM;
 - canals — NRCS, USACE, TVA, USBR;
 - floodplain — NRCS, USACE, TVA, FEMA, USGS, NOAA; and
 - storm drain — local or private.
- c. Environmental constraints including:
 - commitments contained in review documents,
 - fish migration, and
 - wildlife passage.
- d. Design criteria:
 - review Section 9.3 for applicable criteria, and
 - prepare risk assessment or analysis.

Step 2 Determine Hydrology

- a. See Hydrology Chapter.
- b. Minimum data are drainage area map and a discharge-frequency plot.

Step 3 Design Downstream Channel

- a. See Channel Chapter.
- b. Minimum data are cross section of channel and the rating curve for channel.

Step 4 Summarize Data On Design Form

- a. See Chart in Appendix 9.E.
- b. Data from Steps 1-3.

Step 5 Select Design Alternative

- a. See Section 9.3.4 “Design Features.”
- b. Choose culvert material, shape, size and entrance type.

Step 6 Select Design Discharge (Q_d)

- a. See Section 9.3.3 “Design Limitations.”
- b. Determine flood frequency from criteria.
- c. Determine Q from discharge-frequency plot (Step 2).
- d. Divide Q by the number of barrels.

Step 7 Determine Inlet Control Headwater Depth (HW_i)

Use the inlet control nomograph (Appendix 9.D). *Note: A plastic sheet with a matte finish can be used to mark on so that the nomographs can be preserved.*

- a. Locate the size or height on the scale.
- b. Locate the discharge:
 - For a circular shape, use discharge.
 - For a box shape, use Q per foot of width.
- c. Locate HW/D ratio:
 - Use a straight edge.
 - Extend a straight line from the culvert size through the flow rate.
 - Mark the first HW/D scale. Extend a horizontal line to the desired scale and read HW/D and note on Design Form in Appendix 9.E.
- d. Calculate headwater depth (HW_i):
 - Multiply HW/D by D to obtain HW to energy grade line.
 - Neglecting the approach velocity, $HW_i = HW$.
 - Including the approach velocity, $HW_i = HW - \text{approach velocity head}$.

Step 8 Determine Outlet Control Headwater Depth At Inlet (HW_{oi})

- a. Calculate the tailwater depth (TW) using the design flow rate and normal depth (single section) or using a water surface profile.

- b. Calculate critical depth (d_c) using appropriate chart in Appendix 9.D.
 - Locate flow rate and read d_c .
 - d_c cannot exceed D .
 - If $d_c > 0.9D$, consult Handbook of Hydraulics (12) for a more accurate d_c , if needed, because curves are truncated where they converge.
- c. Calculate $(d_c + D)/2$.
- d. Determine (h_o):
 - h_o = the larger of TW or $(d_c + D)/2$.
- e. Determine (k_E):
 - Entrance loss coefficient from Table 9.E-2 in Appendix 9.E.
- f. Determine losses through the culvert barrel (H):
 - Use nomograph (Appendix 9.D) or Equation 9.5 or 9.6 if outside range.
 - Locate appropriate k_E scale.
 - Locate culvert length (L) or (L_1):
 - use (L) if Manning's n matches the n value of the culvert, and
 - use (L_1) to adjust for a different culvert n value:

$$L_1 = L(n_1/n)^2 \quad (9.10)$$

where:

- L_1 = adjusted culvert length, ft
- L = actual culvert length, ft
- n_1 = desired Manning n value
- n = Manning n value on chart

- Mark point on turning line:
 - use a straight edge, and
 - connect size with the length.
 - Read (H):
 - use a straight edge,
 - connect Q and turning point, and
 - read (H) on Head Loss scale.
- g. Calculate outlet control headwater (HW_{oi}):

- Use Equation 9.11; if V_u and V_d are neglected:

$$HW_{oi} = H + h_o - S_o L \quad (9.11)$$

- Use Equations 9.1, 9.4c and 9.6 to include V_u and V_d .
- If HW_{oi} is less than $1.2D$ and control is outlet control:

- the barrel may flow partly full;
- the approximate method of using the greater of tailwater or $(d_c + D)/2$ may not be applicable;
- backwater calculations should be used to check the result; and
- if the headwater depth falls below $0.75D$, the approximate nomograph method shall not be used.

Step 9 Determine Controlling Headwater (HW_c)

- Compare HW_i and HW_{oi} ; use the higher.
- $HW_c = HW_i$, if $HW_i >$ retained for future reference as provided for in the Documentation Chapter.

Step 10 Compute Discharge Over The Roadway (Q_r)

- a. Calculate depth above the roadway (HW_r):
 - $HW_r = HW_c - HW_{ov}$.
 - HW_{ov} = height of road above inlet invert.
- b. If $HW_r \leq 0$, $Q_r = 0$
If $HW_r > 0$, determine C_d from Appendix 9.D.
- c. Determine length of roadway crest (L).
- d. Calculate Q_r using Equation 9.12:

$$Q_r = C_d L HW_r^{1.5} \quad (9.12)$$

Step 11 Compute Total Discharge (Q_t)

$$Q_t = Q_d + Q_r \quad (9.13)$$

Step 12 Calculate Outlet Velocity (V_o) And Depth (d_n)

If inlet control is the controlling headwater:

- a. Calculate flow depth at culvert exit:
 - use normal depth (d_n), or
 - use water surface profile.
- b. Calculate flow area (A).
- c. Calculate exit velocity ($V_o = Q/A$).

If outlet control is the controlling headwater:

a. Calculate flow depth at culvert exit:

- use (d_c) if $d_c > TW$.
- use (TW) if $d_c < TW < D$.
- use (D) if $D < TW$.

b. Calculate flow area (A).

c. Calculate exit velocity (V_o) = Q/A .

Step 13 Review Results

Compare alternative design with constraints and assumptions. If any of the following are exceeded, repeat Steps 5 through 12:

- the barrel must have adequate cover,
- the length shall be close to the approximate length,
- the headwalls and wingwalls must fit site,
- the allowable headwater shall not be exceeded, and
- the allowable overtopping flood frequency shall not be exceeded.

Step 14 Plot Performance Curve

a. Repeat Steps 6 through 12 with a range of discharges.

b. Use the following upper limit for discharge:

- Q_{100} , if $Q_o \leq Q_{100}$.
- Q_{500} , if $Q_o > Q_{100}$.
- Q_{max} , if no overtopping is possible
- Q_{max} = largest flood that can be estimated.

Step 15 Related Designs

Consider the following options (see Sections 9.3.4 and 9.3.5):

- tapered inlets if culvert is in inlet control and has limited available headwater;
- flow routing if a large upstream headwater pool exists (see Section 9.9);
- energy dissipators if V_o is larger than the normal V in the downstream channel (see Energy Dissipator Chapter);
- sediment control storage for sites with sediment concerns (e.g., alluvial fans) (see Erosion and Sediment Control Chapter and Appendix 9.C);
- fish passage (see Section 9.3.5); and/or
- broken-back culverts (see Appendix 9.F).

Step 16 Documentation

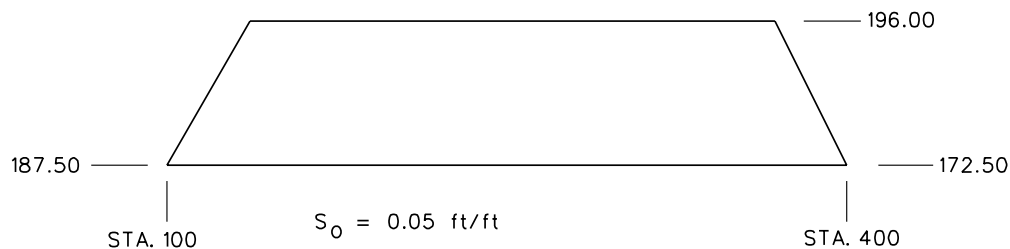
- See Documentation Chapter.
- Prepare report and file with background information.

9.7 NOMOGRAPH DESIGN

The following Example problem follows the Design Procedure Steps described in Section 9.6:

Step 1 Assemble Site Data And Project File

- a. Site survey project file contains:
- USGS, site and location maps;
 - roadway profile; and
 - embankment cross section.



Site visit notes indicate:

- no sediment or debris problems, and
 - no nearby structures.
- b. Studies by other agencies — none.
- c. Environmental, risk assessment shows:
- no buildings near floodplain,
 - no sensitive floodplain values,
 - no FEMA involvement, and
 - convenient detours exist.
- d. Design criteria:
- 50-yr frequency for design, and
 - 100-yr frequency for check.

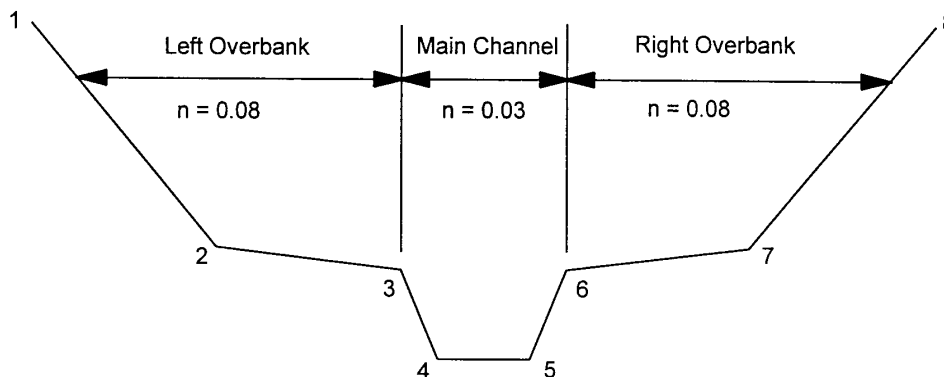
Step 2 Determine Hydrology

USGS regression equations yield:

- $Q_{50} = 400 \text{ ft}^3/\text{s}$
- $Q_{100} = 500 \text{ ft}^3/\text{s}$

Step 3 Design Downstream Channel

Cross section of channel (Slope = 0.05 ft/ft):



Point	Station, ft	Elevation, ft
1	12	180.0
2	22	175.0
3	32	174.5
4	34	172.5
5	39	172.5
6	41	174.5
7	51	175.0
8	61	180.0

The rating curve for the channel calculated by normal depth yields:

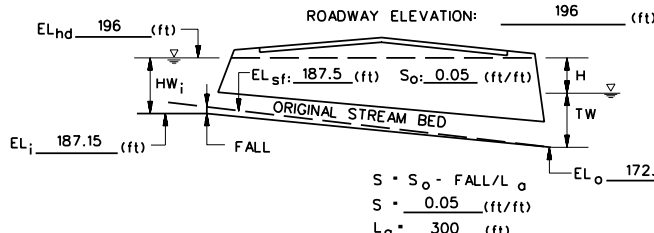
Q (ft ³ /s)	TW (ft)	V (ft/s)
100	1.4	11.1
200	2.1	13.7
300	2.5	16.0
400	2.8	17.5
500	3.1	18.8

Step 4 Summarize Data On Design Form

See Figure 9-11.

Step 5 Select Design Alternative

Shape – box Size – 7 ft x 6 ft
 Material – concrete Entrance – beveled

PROJECT: <u>Example Problem</u> <u>MDM, Chapter 9</u>		STATION: <u>9+00</u> SHEET: <u>1</u> OF <u>1</u>		CULVERT DESIGN FORM DESIGNER / DATE: <u>GCE</u> / <u> </u> REVIEWER / DATE: <u> </u> / <u> </u>																																																																																																																																														
HYDROLOGICAL DATA <input checked="" type="checkbox"/> METHOD: <u>USGS</u> <input type="checkbox"/> DRAINAGE AREA: <u> </u> <input type="checkbox"/> STREAM SLOPE: <u> </u> <input type="checkbox"/> CHANNEL SHAPE: <u> </u> <input type="checkbox"/> ROUTING: <u> </u> <input type="checkbox"/> OTHER: <u> </u>		<div style="text-align: right; margin-bottom: 10px;">ROADWAY ELEVATION: <u>196</u> (ft)</div>  <p style="text-align: right; margin-top: 10px;"> $S = S_o - \text{FALL} / L_o$ $S = 0.05$ (ft/ft) $L_o = 300$ (ft) </p>																																																																																																																																																
DESIGN FLOW/TOTAL WATER <table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <tr> <th>R.I. (YEARS)</th> <th>FLOW (cfs)</th> <th>TW (ft)</th> </tr> <tr> <td><u>50</u></td> <td><u>400</u></td> <td><u>2.8</u></td> </tr> <tr> <td><u>100</u></td> <td><u>500</u></td> <td><u>3.1</u></td> </tr> </table>		R.I. (YEARS)	FLOW (cfs)	TW (ft)	<u>50</u>	<u>400</u>	<u>2.8</u>	<u>100</u>	<u>500</u>	<u>3.1</u>	<table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <tr> <th colspan="15">HEADWATER CALCULATIONS</th> <th rowspan="2">CONTROL HEADWATER ELEVATION</th> <th rowspan="2">OUTLET VELOCITY</th> <th rowspan="2">COMMENTS</th> </tr> <tr> <th colspan="2">CULVERT DESCRIPTION:</th> <th>TOTAL FLOW</th> <th>FLOW PER BARREL</th> <th colspan="5">INLET CONTROL</th> <th colspan="5">OUTLET CONTROL</th> </tr> <tr> <th>MATERIAL - SHAPE - SIZE - ENTRANCE</th> <th>Q (cfs)</th> <th>Q/B (cfs)</th> <th>HW₁/D</th> <th>HW₁</th> <th>FALL</th> <th>EL_{h1}</th> <th>TW</th> <th>d_c</th> <th>d_c/2</th> <th>h₂</th> <th>h₂</th> <th>H</th> <th>EL_{h2}</th> <th>EL_{h2}</th> </tr> <tr> <td>RCB- 7x6- Bevel</td> <td><u>400</u></td> <td><u>57</u></td> <td><u>1.27</u></td> <td><u>7.6</u></td> <td><u>0</u></td> <td><u>195.1</u></td> <td><u>2.8</u></td> <td><u>4.7</u></td> <td><u>5.4</u></td> <td><u>5.4</u></td> <td><u>.2</u></td> <td><u>2.8</u></td> <td><u>190.7</u></td> <td><u>195.1</u></td> <td><u>32</u></td> <td><u>195.1' < 196' ok</u></td> </tr> <tr> <td></td> <td><u>500</u></td> <td><u>72</u></td> <td><u>1.56</u></td> <td><u>9.4</u></td> <td><u>0</u></td> <td><u>196.9</u></td> <td><u>3.1</u></td> <td><u>5.4</u></td> <td><u>5.7</u></td> <td><u>5.7</u></td> <td><u>.2</u></td> <td><u>4.3</u></td> <td><u>192.2</u></td> <td><u>196.9</u></td> <td><u>34</u></td> <td><u>> 196' Calc Q_r</u></td> </tr> <tr> <td>Performance Curve</td> <td><u>100</u></td> <td><u>14</u></td> <td><u>.46</u></td> <td><u>2.8</u></td> <td><u>0</u></td> <td><u>190.3</u></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td><u>200</u></td> <td><u>29</u></td> <td><u>.78</u></td> <td><u>4.7</u></td> <td><u>0</u></td> <td><u>192.2</u></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td><u>300</u></td> <td><u>43</u></td> <td><u>1.01</u></td> <td><u>6.1</u></td> <td><u>0</u></td> <td><u>193.6</u></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> </table>				HEADWATER CALCULATIONS															CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS	CULVERT DESCRIPTION:		TOTAL FLOW	FLOW PER BARREL	INLET CONTROL					OUTLET CONTROL					MATERIAL - SHAPE - SIZE - ENTRANCE	Q (cfs)	Q/B (cfs)	HW ₁ /D	HW ₁	FALL	EL _{h1}	TW	d _c	d _c /2	h ₂	h ₂	H	EL _{h2}	EL _{h2}	RCB- 7x6- Bevel	<u>400</u>	<u>57</u>	<u>1.27</u>	<u>7.6</u>	<u>0</u>	<u>195.1</u>	<u>2.8</u>	<u>4.7</u>	<u>5.4</u>	<u>5.4</u>	<u>.2</u>	<u>2.8</u>	<u>190.7</u>	<u>195.1</u>	<u>32</u>	<u>195.1' < 196' ok</u>		<u>500</u>	<u>72</u>	<u>1.56</u>	<u>9.4</u>	<u>0</u>	<u>196.9</u>	<u>3.1</u>	<u>5.4</u>	<u>5.7</u>	<u>5.7</u>	<u>.2</u>	<u>4.3</u>	<u>192.2</u>	<u>196.9</u>	<u>34</u>	<u>> 196' Calc Q_r</u>	Performance Curve	<u>100</u>	<u>14</u>	<u>.46</u>	<u>2.8</u>	<u>0</u>	<u>190.3</u>												<u>200</u>	<u>29</u>	<u>.78</u>	<u>4.7</u>	<u>0</u>	<u>192.2</u>												<u>300</u>	<u>43</u>	<u>1.01</u>	<u>6.1</u>	<u>0</u>	<u>193.6</u>										
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TECHNICAL FOOTNOTES: (1) USE Q/H ₂ FOR BOX CULVERTS (2) HW ₁ /D = HW ₁ /D OR HW ₁ /D FROM DESIGN CHARTS (3) FALL = HW ₁ - (EL _{hd} - EL _{sf}); FALL IS ZERO FOR CULVERTS ON GRADE (4) EL _{h2} = HW ₁ + EL ₁ (INLET OF INLET CONTROL SECTION) (5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL (6) h ₂ = TW or (d _c + D/2) (WHICHEVER IS GREATER) (7) H = $\left[1 + h_2 \left(\frac{2500 L}{R^{1.33}} \right) \right] v^2 / 2g$ (8) EL _{h2} = EL _{h1} + H + h ₂																																																																																																																																																		
SUBSCRIPT DEFINITIONS: a. APPROXIMATE c. CULVERT PAGE d. DESIGN HEADWATER h ₂ . HEADWATER IN INLET CONTROL h ₂ . HEADWATER IN OUTLET CONTROL i. INLET CONTROL SECTION o. OUTLET r. STREAMBED AT CULVERT PAGE s. THIS SHEET		COMMENTS / DISCUSSION: Use 500 cfs in culvert: $Q_r = C_d L H W_r^{1.5} = 3.03(200')(9)^{1.5} = 520 \text{ cfs}$ $Q_r = 500 + 520 = 1020 \text{ cfs}$										CULVERT BARREL SELECTED: SIZE: <u>7x6</u> SHAPE: <u>RCB</u> MATERIAL: <u> </u> ENTRANCE: <u>Bevel</u>																																																																																																																																						

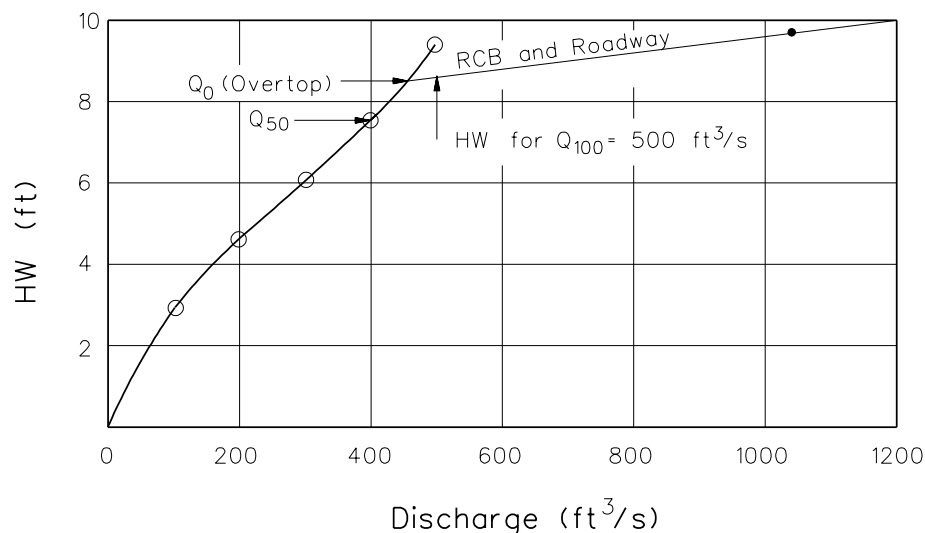


FIGURE 9-11 — Chart 17 and Performance Curve for Design Example

Step 6 Select Design Discharge

$$Q_d = Q_{50} = 400 \text{ ft}^3/\text{s}$$

Step 7 Determine Inlet Control Headwater Depth (HW_i)

Use inlet control nomograph – Chart 10:

- a. $D = 6 \text{ ft}$
- b. $Q/B = 400/7 = 57$
- c. $HW/D = 1.33$ for $\frac{3}{4}$ in chamfer
 $HW/D = 1.27$ for 45° bevel
- d. $HW_i = (HW/D)D = (1.27)6 = 7.6 \text{ ft}$ (Neglect the approach velocity).

Step 8 Determine Outlet Control Headwater Depth At Inlet (HW_{oi})

- a. $TW = 2.8 \text{ ft}$ for $Q_{50} = 400 \text{ ft}^3/\text{s}$
- b. $d_c = 4.7 \text{ ft}$ from Chart 14
- c. $(d_c + D)/2 = (4.7 + 6)/2 = 5.4 \text{ ft}$
- d. $h_o =$ the larger of TW or $(d_c + D)/2$
 $h_o = (d_c + D)/2 = 5.4 \text{ ft}$
- e. $k_E = 0.2$ from Table 9.E-2
- f. Determine (H) — use Chart 15:
 - k_E scale = 0.2
 - culvert length $(L) = 300 \text{ ft}$
 $n = 0.012$ (same as on chart)
 - area = 42 ft^2
 - $H = 2.8 \text{ ft}$
- g. $HW_{oi} = H + h_o - S_oL = 2.8 + 5.4 - (0.05)300 = -6.8 \text{ ft}$

HW_{oi} is less than $1.2D$, but control is inlet control. Outlet control computations are for comparison only.

Step 9 Determine Controlling Headwater (HW_c)

- a. $HW_c = HW_i = 7.6 \text{ ft} > HW_{oi} = -6.8 \text{ ft}$
- b. The culvert is in inlet control.

Step 10 Compute Discharge Over Roadway (Q_r)

- a. Calculate depth above the roadway:

$$HW_r = HW_c - HW_{ov} = 7.6 - 8.5 = -0.9 \text{ ft}$$

- b. If $HW_r \leq 0$, $Q_r = 0$

Step 11 Compute Total Discharge (Q_t)

$$Q_t = Q_d + Q_r = 400 \text{ ft}^3/\text{s} + 0 = 400 \text{ ft}^3/\text{s}$$

Step 12 Calculate Outlet Velocity (V_o) and Depth (d_n)

INLET CONTROL:

- a. Calculate normal depth (d_n):

$$\begin{aligned} Q &= (1.486/n)A R^{2/3} S^{1/2} = 400 \text{ ft}^3/\text{s} \\ &= (123.8)(7)(d_n)[7(d_n)/(7 + 2d_n)]^{2/3}(0.05)^{0.5} \\ &= (7)(d_n)[7(d_n)/(7 + 2d_n)]^{2/3} = 14.4 \end{aligned}$$

$$\begin{aligned} \text{try } d_n &= 2.0 \text{ ft}, 16.5 > 14.4 \\ \text{use } d_n &= 1.8 \text{ ft}, 14.1 \approx 14.4 \end{aligned}$$

b. $A = (1.8)7 = 12.6 \text{ ft}^2$

c. $V_o = Q/A = 400/12.6 = 31.7 \text{ ft/s}$

Step 13 Review Results

Compare alternative design with constraints and assumptions. If any of the following are exceeded, repeat Steps 5 through 12:

- barrel has $(8.5 - 6) = 2.5 \text{ ft}$ of cover,
- $L = 300 \text{ ft}$ is OK, since inlet control,
- headwalls and wingwalls fit site,
- allowable headwater $(8.5 \text{ ft}) > 7.6 \text{ ft}$ is OK, and
- overtopping flood frequency $> 50\text{-yr}$.

Step 14 Plot Performance Curve

Use Q_{100} for the upper limit. Steps 6 through 12 should be repeated for each discharge used to plot the performance curve. These computations are provided on the computation form, Chart 17, that follows this Example (see Figure 9-11).

Step 15 Related Designs

Consider the following options (see Sections 9.3.4 and 9.3.5):

- a. Consider tapered inlets; culvert is in inlet control and has limited available headwater:
- No flow routing; a small upstream headwater pool exists.
 - Consider energy dissipators since $V_o = 31.7 \text{ ft/s} > 18.0 \text{ ft/s}$ in the downstream channel.
 - No sediment problem.
 - No fishery.

Step 16 Documentation

Report prepared and background filed.

9.8 MICROCOMPUTER SOLUTION

9.8.1 Overview

Culvert hydraulic analysis can also be accomplished with the aid of the HYDRAIN software (7). The following example has been produced using the HY8 Culvert Analysis Microcomputer Program (6). It is the computer solution of the data provided in Section 9.7. The screens shown may not match exactly the current version of HY8 because some editorial changes have been made so that the screens will fit in this text.

9.8.2 Data Input

After creating a file, the user will be prompted for the discharge range, site data and culvert shape, size, material and inlet type. The discharge range for this example will be from 0 to 500 ft^3/s . The site data are entered by providing culvert invert data. If embankment data points are input, the program will fit the culvert in the fill and subtract the appropriate length.

9.8.2.1 Culvert Data

As an initial size estimate, try a 5-ft \times 5-ft concrete box culvert. For the culvert, assume that a conventional inlet with 1:1 bevels and 45° wingwalls will be used. As each group of data are entered, the user is allowed to edit any incorrect entries. The following is how the screen that summarizes the culvert information will look.

CULVERT FILE: MDMEX1	FHWA CULVERT ANALYSIS	DATE: 02-06-2003
TAILWATER FILE: TWEX1	HY8, VERSION 6.1	CULVERT NO. 1 OF 1

NO	ITEM	CULVERT DATA
----	------	--------------

<1>	BARREL SHAPE:	BOX
<2>	BARREL SIZE:	7 ft x 6 ft
<3>	BARREL MATERIAL:	CONCRETE
<4>	MANNING'S N:	0.012
<5>	INLET TYPE:	CONVENTIONAL
<6>	INLET EDGE AND WALL	1:1 BEVEL (45 DEG. FLARE)
<7>	INLET DEPRESSION:	NONE

<ENTER> TO CONTINUE	<NUMBER> TO EDIT ITEM
---------------------	-----------------------

1-Help	2-Prog	3	4	5-End	6	7-Edit	8	9-DOS	10
--------	--------	---	---	-------	---	--------	---	-------	----

9.8.2.2 Channel Data

Next, the program will prompt for data pertaining to the channel so that tailwater elevations can be determined. Referring to the problem statement, the channel is irregularly shaped and can be described by the eight coordinates listed. After opening the irregular channel file, the user will be prompted for channel slope (0.05), number of cross-section coordinates (8) and subchannel option. The subchannel option in this case would be option (2), left and right overbanks (n = 0.08) and main channel (n = 0.03).

IRREGULAR CHANNEL CROSS-SECTION					
---------------------------------	--	--	--	--	--

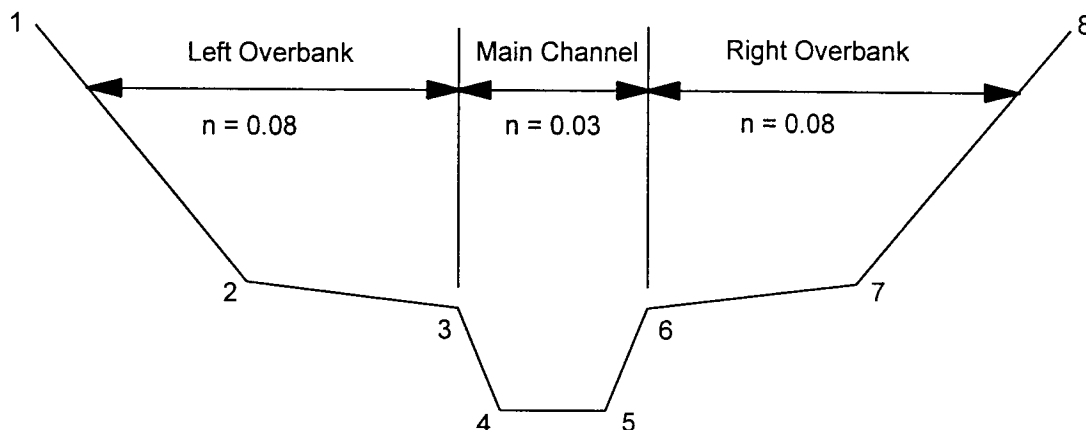
CROSS-SECTION	X	Y	CROSS-SECTION	X	Y
COORD. NO.	(ft)	(ft)	COORD. NO.	(ft)	(ft)
1	12	180.0	5	39	172.5
2	22	175.0	6	41	174.5
3	32	174.5	7	51	175.0
4	34	172.5	8	61	180.0

<NUMBER> TO EDIT COORDINATES	<I> <D> TO INSERT OR DELETE
<ENTER> TO CONTINUE	<P> TO PLOT CROSS-SECTION

1-Help	2-Prog	3	4	5-End	6	7-Edit	8	9-DOS	10
--------	--------	---	---	-------	---	--------	---	-------	----

The next prompt, for channel boundaries, refers to the number of the coordinate pair defining the left subchannel boundary and the number of the coordinate pair defining the right subchannel boundary. The boundaries for this Example are the 3rd and 6th coordinates. After this is input, the program prompts for channel coordinates. Once these are entered, pressing (P) will cause the computer to display the channel cross section (see Figure 9-12). The user can

easily identify any input errors by glancing at the plot. To return to the data input screens, press any key. If data are correct, press (return). One can then enter the roughness data for the main channel and overbanks.



**FIGURE 9-12 — Channel Cross Section
(Microcomputer Example)**

9.8.3 Rating Curve

The program now has enough information to develop a uniform flow rating curve for the channel and provide the user with a list of options. By selecting option (T) on the Irregular Channel Data Menu, the program computes the rating curve data and displays the following table. Selecting option (I) will permit the user to interpolate data between calculated points.

CULVERT FILE: CULEX1B			FHWA CULVERT ANALYSIS			DATE: 02-06-2003	
TAILWATER FILE: EXITW			HY8, VERSION 6.1			CULVERT NO. 1 OF 1	
NO.	FLOW (cfs)	W.S.E. (ft)	FROUDE NUMBER	DEPTH (ft)	VEL. (f/s)	SHEAR (psf)	
1	0.00	172.50	0.000	0.00	0.00	0.00	
2	50.00	173.45	1.757	0.95	9.02	2.30	
3	100.00	173.91	1.823	1.41	11.13	3.14	
4	150.00	174.28	1.859	1.78	12.52	3.75	
5	200.00	174.57	1.892	2.07	13.71	4.30	
6	250.00	174.80	1.933	2.30	14.93	4.89	
7	300.00	174.99	1.965	2.49	15.97	5.40	
8	350.00	175.15	1.990	2.65	16.77	5.82	
9	400.00	175.30	2.011	2.80	17.51	6.20	
10	450.00	175.44	2.030	2.94	18.19	6.57	
11	500.00	175.56	2.047	3.06	18.81	6.90	

Note: Shear stress was calculated using R.

PRESS <D> FOR DATA <P> TO PLOT RATING CURVE
 <ESC> FOR CHANNEL SHAPE MENU <ENTER> TO CONTINUE

1-Help 2-Prog 3 4 5-End 6 7-Edit 8 9-DOS 10

The Tailwater Rating Curve Table consists of tailwater elevation (T.W.E.) at normal depth, natural channel velocity (Vel.) and the shear stress at the bottom of the channel for various flow rates. At the design flow rate of 400 ft³/s, the tailwater elevation will be 175.30 ft. The channel velocity will be 17.51 ft/s, and the shear will be 6.20 lb/ft². This information will be useful in the design of channel linings if they are needed. Entering (P) will cause the computer to display the rating curve for the channel. This curve, shown in Figure 9-13, is a plot of tailwater elevation vs. flow rate at the exit of the culvert.

9.8.4 Roadway Data

The next prompts are for the roadway profile, so that an overtopping analysis can be performed. The hand solution, Section 9.7, assumed a constant roadway elevation. The roadway profile is a sag vertical curve, which will require nine coordinates to define. Once these coordinates are input, the profile will be displayed when (P) is entered, as illustrated in Figure 9-14. The other data required for overtopping analysis are roadway surface or weir coefficient and the embankment top width. For this Example, the roadway is paved with an embankment width of 50 ft.

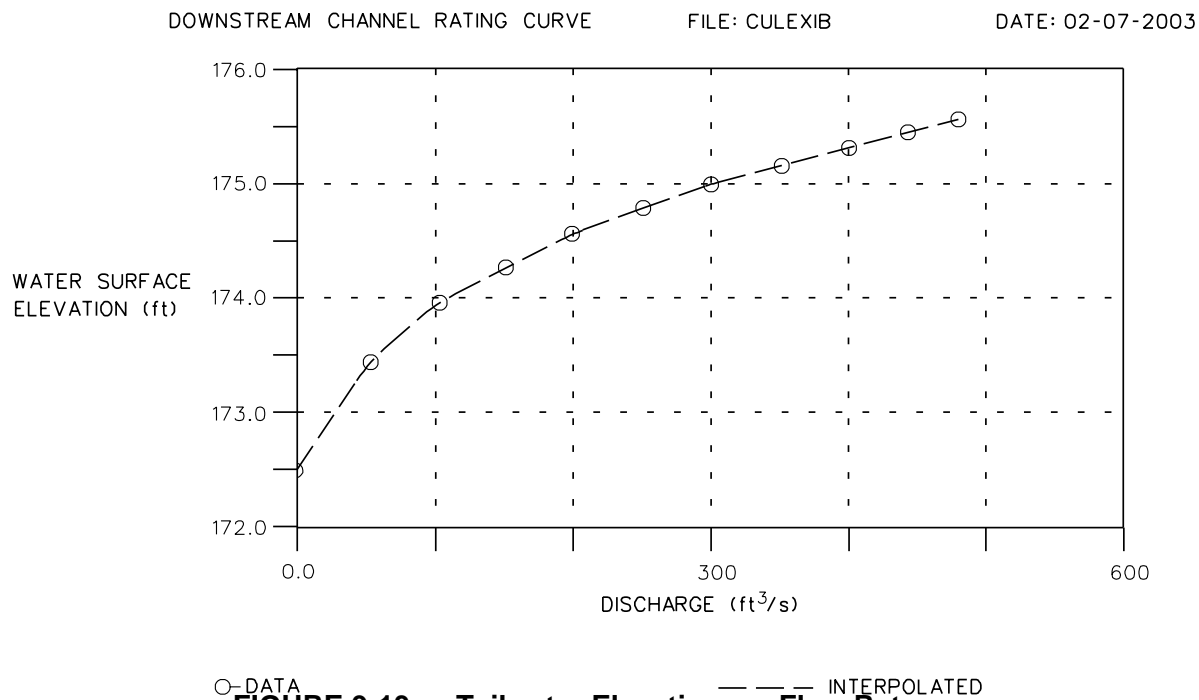
9.8.5 Data Summary

All the data has now been entered and the summary table is displayed as shown below. At this point, any of the data can be changed or the user can save the data and continue by pressing (Enter), which will bring up the Culvert Program Options Menu.

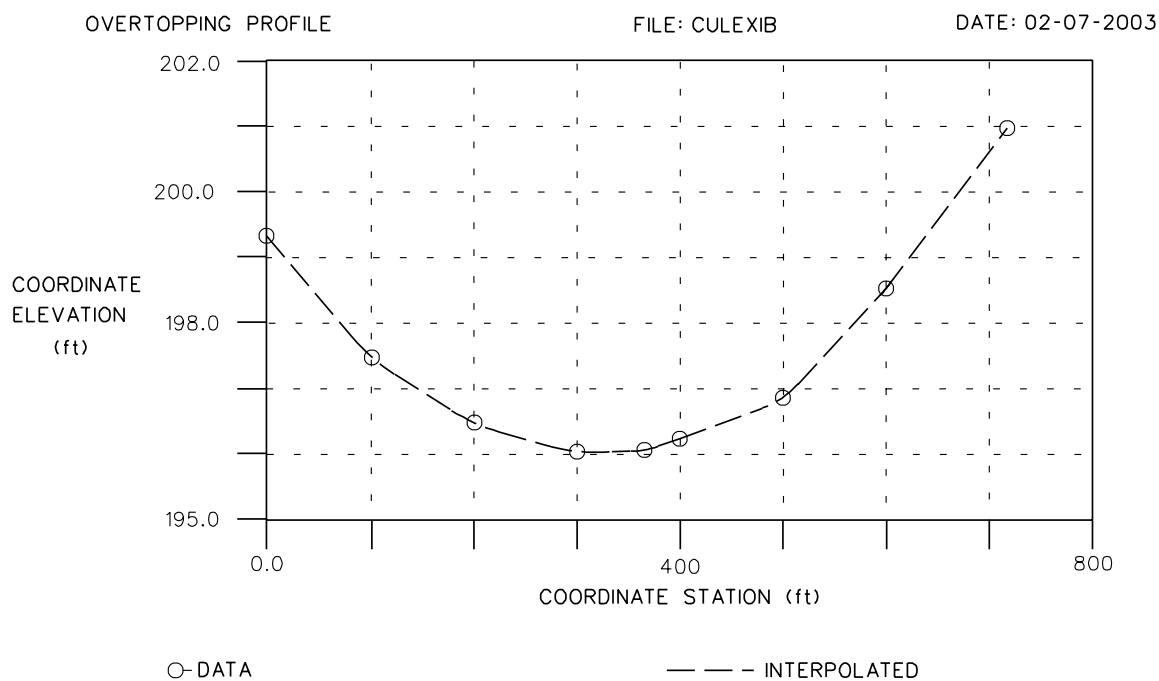
CULVERT FILE: CULEX1B			FHWA CULVERT ANALYSIS				DATE: 02-06-2003		
TAILWATER FILE: EXITW			HY8, VERSION 6.1				CULVERT NO. 1 OF 1		
SUMMARY TABLE									
C	<S>	SITE DATA		<C> CULVERT SHAPE, MATERIAL, INLET					
U									
L	INLET	OUTLET	CULVERT	BARRELS					
V	ELEV.	ELEV.	LENGTH	SHAPE	SPAN	RISE	MANNING	INLET	
NO.	(ft)	(ft)	(ft)	MATERIAL	(ft)	(ft)	n	TYPE	
1	187.50	172.50	300.37	1 - RCB	5.00	5.00	.012	CONVENTIONAL	
2									
PRESS TO REVIEW				PRESS TO					
<C> Culvert Data				<E> Edit Culvert Size					
<D> Discharge Data				<M> Minimize Culvert Span					
<R> Roadway Data				<A> Add or Delete Culverts					
<S> Site Data				<N> Edit Number of Barrels					
<T> Tailwater Rating Curve				<F> File – Save or Rename					
<ENTER> To Save & Exit				<ESC> For File Menu					
1-Help	2-Prog	3	4	5-End	6	7-Edit	8	9-DOS 10	

9.8.6 Performance Curve (5 ft x 5 ft) RCB

From the Culvert Program Options Menu, the culvert performance curve table can be obtained by selecting option (S). When option (S) is selected, the program will compute the performance curve table without considering overtopping in the analysis. Because this 5 ft x 5 ft culvert is a



**FIGURE 9-13 — Tailwater Elevation vs. Flow Rate
(Microcomputer Example)**



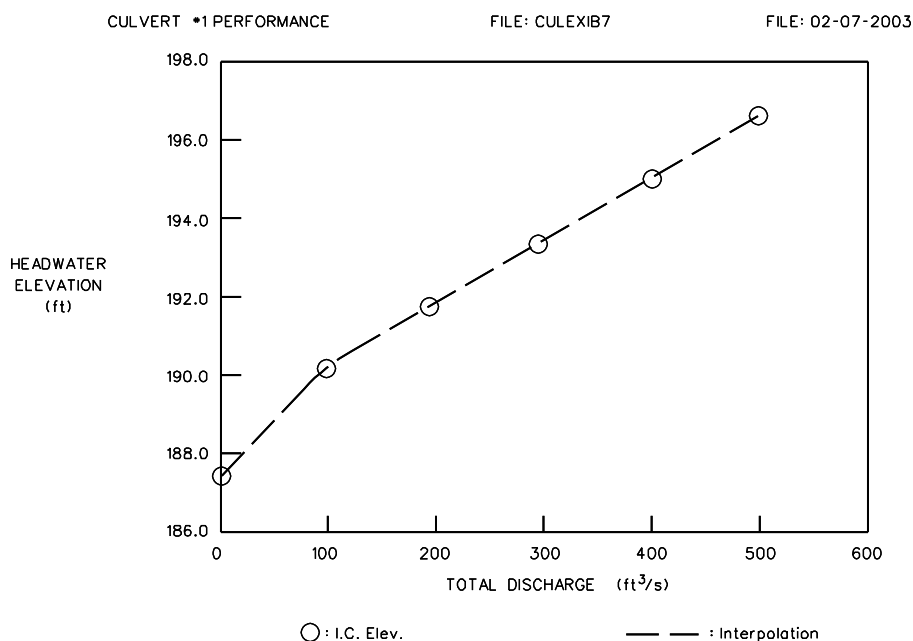
**FIGURE 9-14 — Roadway Profile
(Microcomputer Example)**

PERFORMANCE CURVE FOR CULVERT 1 - 1(6.00 (ft) BY 6.00 (ft)) RCB

DIS- CHARGE FLOW (cfs)	HEAD- WATER ELEV. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	FLOW TYPE <F4>	NORMAL DEPTH (ft)	CRIT. DEPTH (ft)	OUTLET DEPTH (ft)	TW DEPTH (ft)	OUTLET VEL. (fps)	TW VEL. (fps)
0.00	187.50	0.00	0.00	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
50.00	189.34	1.84	1.84	1-S2n	0.48	1.29	0.39	0.95	21.11	9.02
100.00	190.43	2.93	2.93	1-S2n	0.79	2.06	0.76	1.41	22.07	11.13
150.00	191.44	3.94	3.94	1-S2n	1.05	2.69	0.99	1.78	25.17	12.52
200.00	192.37	4.87	4.87	1-S2n	1.28	3.26	1.34	2.07	24.83	13.71
250.00	193.27	5.77	5.77	1-S2n	1.49	3.79	1.59	2.30	26.27	14.93
300.00	194.18	6.68	6.68	5-S2n	1.70	4.28	1.85	2.49	27.10	15.97
350.00	195.12	7.62	7.62	5-S2n	1.90	4.74	2.09	2.65	27.94	16.77
400.00	196.12	8.62	8.62	5-S2n	2.08	5.18	2.33	2.80	28.62	17.51
450.00	197.21	9.71	9.71	5-S2n	2.27	5.60	2.56	2.94	29.27	18.19
500.00	198.40	10.90	-3.22	6-S2n	2.46	6.00	2.79	3.06	29.87	18.81
El inlet face invert			187.50 ft			El outlet invert			172.50 ft	
El. Inlet throat invert			0.00 ft			El. inlet crest			0.00 ft	
PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE										
<P> TO PLOT <I> FOR IMPROVED INLET TABLE										
1-Help	2-Prog	3	4	5-End	6	7-Edit	8	9-DOS	10	

9.8.8 Performance Curve (7 ft x 6 ft) RCB

Because the design headwater criterion has still not been met, another size must be selected. Try a 7 ft x 6 ft culvert and modify the file accordingly. The resulting performance table shown below indicates that the design headwater will not be exceeded at 400 ft³/s. However, the headwater elevation of 196.00 ft at 500 ft³/s indicates that some overtopping will occur due to the 100-yr storm.



**FIGURE 9-15 — INLET CONTROL HEADWATER
(Microcomputer Example)**

PERFORMANCE CURVE FOR CULVERT 1 - 1(7.00 (ft) BY 6.00 (ft)) RCB

DIS-CHARGE FLOW (cfs)	HEAD-WATER ELEV. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	FLOW TYPE <F4>	NORMAL DEPTH (ft)	CRIT. DEPTH (ft)	OUTLET DEPTH (ft)	TW DEPTH (ft)	OUTLET VEL. (fps)	TW VEL. (fps)
0.00	187.50	0.00	0.00	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
50.00	189.16	1.66	1.66	1-S2n	0.40	1.17	0.37	0.95	19.39	9.02
100.00	190.14	2.64	2.64	1-S2n	0.71	1.85	0.65	1.41	21.82	11.13
150.00	191.02	3.52	3.52	1-S2n	0.92	2.43	0.96	1.78	22.32	12.52
200.00	191.85	4.35	4.35	1-S2n	1.13	2.94	1.18	2.07	24.13	13.71
250.00	192.63	5.13	5.13	1-S2n	1.32	3.42	1.40	2.30	25.58	14.93
300.00	193.40	5.90	5.90	1-S2n	1.49	3.86	1.61	2.49	26.66	15.97
350.00	194.18	6.68	6.68	5-S2n	1.66	4.28	1.82	2.65	27.55	16.77
400.00	194.98	7.48	7.48	5-S2n	1.82	4.67	2.02	2.80	28.24	17.51
450.00	195.83	8.33	8.33	5-S2n	1.98	5.05	2.22	2.94	28.89	18.19
500.00	196.74	9.24	9.24	5-S2n	2.13	5.42	2.42	3.06	29.48	18.81
El inlet face invert			187.50 ft		El outlet invert			172.50 ft		
El. Inlet throat invert			0.00 ft		El. inlet crest			0.00 ft		
PRESS: <KEY> TO CONTINUE				<W> FOR PROFILE TABLE						
<P> TO PLOT			<I> FOR IMPROVED INLET TABLE							
1-Help	2-Prog	3	4	5-End	6	7-Edit	8	9-DOS	10	

9.8.9 Minimize Culvert

Rather than using a series of trials to reduce the culvert headwater to an acceptable level, as in the preceding examples, the “Minimize Culvert Span” feature of HY8 can be used. This feature allows the designer to use HY8 as a tool to perform culvert design for circular, box, elliptical and arch shape culverts based on a user’s defined allowable headwater elevation, assuming no overtopping. This feature can be activated by selecting letter “M.” Once this option is selected, the user inputs the allowable headwater elevation. That elevation will be the basis for adjusting the user’s defined culvert size for the design discharge. The program will adjust the culvert span by increasing or decreasing by 0.5-ft increments. It will compute the headwater elevation for the span and compare it with the user’s defined allowable headwater. If the computed headwater elevation is lower than or equal to the defined allowable headwater elevation, the minimization routine will stop, and the adjusted culvert can be used for the remainder of the program. Several hydraulic parameters are also computed while performing the minimization routine. These hydraulic parameters, which are part of the output of the minimization routine table, as shown below, must be printed from this screen because they are not printed with the output listing routine.

CULVERT FILE: CULEX1B7
TAILWATER FILE: TWEX1

FHWA CULVERT ANALYSIS
HY8, VERSION 6.1

DATE:02-07-2003
CULVERT NO. 1 OF 1

C <S> SITE DATA		SUMMARY TABLE						
U		<C> CULVERT SHAPE, MATERIAL, INLET						
L INLET	OUTLET	CULVERT	BARRELS					
V ELEV.	ELEV.	LENGTH	3SHAPE	SPAN	RISE	MANNING		INLET
NO (ft)	(ft)	(ft)	MATERIAL	(ft)	(ft)	n		TYPE
1 187.50	172.50	300.37	1 - RCB	6.5	6.00	.012		CONVENTIONAL

HEADWATER ELEVATION (ft)	FLOW VELOCITY (ft/s)	FLOW DEPTHS (ft)
ENTER ALLOWABLE = 196.00	V culvert = 28.49	CULVERT = 2.16
CONTROLLING = 195.50	V channel = 17.51	CHANNEL = 2.80
INLET CONTROL = 195.50	Q (ft ³ /s) = 400.00	NORMAL = 1.94
OUTLET CONTROL = 195.50	SLOPE = 0.0500	CRITICAL = 4.91

MAXIMUM HEADWATER <ENTER> TO RETURN <S> TO SAVE FILE
<H> TO CHANGE HEADWATER

1-Help 2-Prog 3 4 5-End 6 7-Edit 8 9-DOS 10

This feature proves to be a time saver for designers because it avoids the need for repetitively editing a culvert size to obtain a controlling headwater elevation.

9.8.10 Overtopping Performance Curve (7 ft x 6 ft) RCB

Returning to the 7 ft x 6 ft culvert, to determine the amount of overtopping and the actual headwater, from the Culvert Program Options Menu, select (O) for overtopping. A Summary of Culvert Flows will appear on the screen, as shown below:

HY8, VERSION 6.1

SUMMARY OF CULVERT FLOWS (cfs)

FILE: CULEX1B7

DATE: 02-07-2003

ELEV(ft)	TOTAL	1	2	3	4	5	6	ROADWAY	ITR
187.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1
189.16	50.0	50.0	0.0	0.0	0.0	0.0	0.0	0.00	1
190.14	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.00	1
191.02	150.0	150.0	0.0	0.0	0.0	0.0	0.0	0.00	1
191.85	200.0	200.0	0.0	0.0	0.0	0.0	0.0	0.00	1
192.63	250.0	250.0	0.0	0.0	0.0	0.0	0.0	0.00	1
193.40	300.0	300.0	0.0	0.0	0.0	0.0	0.0	0.00	1
194.18	350.0	350.0	0.0	0.0	0.0	0.0	0.0	0.00	1
194.98	400.0	400.0	0.0	0.0	0.0	0.0	0.0	0.00	1
195.83	450.0	450.0	0.0	0.0	0.0	0.0	0.0	0.00	1
196.21	500.0	470.8	0.0	0.0	0.0	0.0	0.0	25.20	8
196.00	459.4	459.4	0.0	0.0	0.0	0.0	0.0	OVERTOPPING	

PRESS: <P> TO PLOT TOTAL RATING CURVE

<T> TO DISPLAY TABLE FOR EACH CULVERT

<E> TO DISPLAY ERROR TABLE

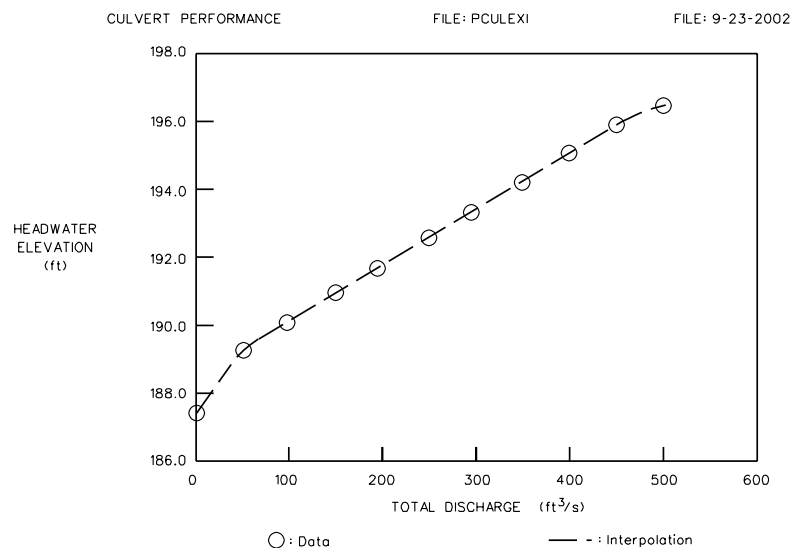
<R> TO PRINT REPORT Output stored in CULEX1B7.PC

<H> TO RETURN TO HEADWATER TABLE

<ENTER> TO RETURN TO OPTION MENU

1-Help 2-Prog 3 4 5-End 6 7-Edit 8 9-DOS 10

This computation table is used when overtopping and/or multiple culvert barrels are used. It shows the headwater, total flow rate, the flow through each barrel and overtopping flow and the number of iterations it took to balance the flows. From this information, a total (culvert and overtopping) performance curve, shown in Figure 9-16, can be obtained by selecting option (P). This curve is a plot of the headwater elevation vs. the total flow rate that indicates how the culvert or group of culverts will perform over the selected range of discharges. It is especially useful for comparing the effects of various combinations of culverts.



**FIGURE 9-16 — Total Performance Curve (Headwater Elevation vs. Total Flow Rate)
(Microcomputer Example)**

9.8.11 Review

From the Summary table, when the total flow is 500 ft³/s, 470.8 ft³/s passes through the culvert and 25.20 ft³/s flows over the road. The headwater elevation will be 196.21 ft. Assume that, in this case, overtopping at the 100-yr frequency can be tolerated, and the 7 ft x 6 ft culvert will be used. When overtopping occurs, the performance of the culvert will differ from that without overtopping. By selecting option (T), the culvert performance data can be obtained. The user also has the option to plot these data.

Referring to the performance curve data shown below, the outlet velocity at 400 ft³/s is 28.24 ft/s. Because the tailwater rating curve generated previously indicates that the natural channel velocity at 400 ft³/s is 17.51 ft/s, an energy dissipator is warranted.

PERFORMANCE CURVE FOR CULVERT 1 - 1(7.00 (ft) BY 6.00 (ft)) RCB

DIS-CHARGE FLOW (ft³/s)	HEAD-WATER ELEV. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	FLOW TYPE <F4>	NORMAL DEPTH (ft)	CRIT. DEPTH (ft)	OUTLET DEPTH (ft)	TW DEPTH (ft)	OUTLET VEL. (ft/s)	TW VEL. (ft/s)
0.00	187.50	0.00	0.00	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
50.00	189.16	1.66	1.66	1-S2n	0.40	1.17	0.37	0.95	19.39	9.02
100.00	190.14	2.64	2.64	1-S2n	0.71	1.85	0.65	1.41	21.82	11.13
150.00	191.02	3.52	3.52	1-S2n	0.92	2.43	0.96	1.78	22.32	12.52
200.00	191.85	4.35	4.35	1-S2n	1.13	2.94	1.18	2.07	24.13	13.71
250.00	192.63	5.13	5.13	1-S2n	1.32	3.42	1.40	2.30	25.58	14.93
300.00	193.40	5.90	5.90	1-S2n	1.49	3.86	1.61	2.49	26.66	15.97
350.00	194.18	6.68	6.68	5-S2n	1.66	4.28	1.82	2.65	27.55	16.77
400.00	194.98	7.48	7.48	5-S2n	1.82	4.67	2.02	2.80	28.24	17.51
450.00	195.83	8.33	8.33	5-S2n	1.98	5.05	2.22	2.94	28.89	18.19
470.77	196.20	8.70	8.70	5-S2n	2.04	5.21	2.30	3.06	29.25	18.81
El inlet face invert			187.50 ft			El outlet invert			172.50 ft	
El. Inlet throat invert			0.00 ft			El. inlet crest			0.00 ft	
<P> TO PLOT <I> FOR IMPROVED INLET TABLE										
1-Help	2-Prog	3	4	5-End	6	7-Edit	8	9-DOS	10	

By pressing <enter>, the program returns to the Summary of Culvert Flows menu. Selecting option (E), a Summary of Iterative Solution Errors is produced. This table, shown below, lists the amount of error present in the solution for a flow rate of 500 ft³/s which is 4.02 ft³/s.

SUMMARY OF ITERATIVE SOLUTION ERRORS

FILE: CULEX1B7

DATE: 02-07-2003

HEAD ELEV (ft)	HEAD ERROR (ft)	TOTAL FLOW (cfs)	FLOW ERROR (cfs)	% FLOW ERROR
187.50	0.000	0.00	0.00	0.00
189.16	0.000	50.00	0.00	0.00
190.14	0.000	100.00	0.00	0.00
191.02	0.000	150.00	0.00	0.00
191.85	0.000	200.00	0.00	0.00
192.63	0.000	250.00	0.00	0.00
193.40	0.000	300.00	0.00	0.00
194.18	0.000	350.00	0.00	0.00
194.98	0.000	400.00	0.00	0.00
194.83	0.000	450.00	0.00	0.00
196.21	-0.006	500.00	4.02	0.80

<1> TOLERANCE (ft) = 0.010					<2> TOLERANCE (%) = 1.000				
----------------------------	--	--	--	--	---------------------------	--	--	--	--

PRESS <NUMBER> TO EDIT					DISPLAY ITERATIONS				
PRESS <ENTER> TO RETURN					<3> FOR HEADWATER - NO				
PRESS <ESC> TO RECOMPUTE					<4> FOR DISCHARGE - NO				
					<5> TONE AT FINISH - NO				
1-Help	2-Prog	3	4	5-End	6	7-Edit	8	9-DOS	10

9.9 FLOOD ROUTING CULVERT DESIGN

9.9.1 Introduction

Flood routing through a culvert is a practice that evaluates the effect of temporary upstream ponding caused by the culvert's backwater. By not considering flood routing, it is possible that the findings from culvert analyses will be conservative. If the selected allowable headwater is considered acceptable without flood routing, then costly over design of both the culvert and outlet protection may result, depending on the amount of temporary storage involved.

These special considerations associated with culvert flood routing are discussed in the following subsections:

- *Culvert Replacement Applications* — Normally, a smaller culvert may be used for the same headwater condition.
- *Environmental* — Evaluating environmental concerns may be more realistic.
- *Flood Hazards* — A routing culvert design may require less land for an upstream easement and assessments of potential flood hazards may be more realistic.
- *Sediment* — Estimation of sediment accumulation is required.
- *Limitations* — Temporary storage must be available.

9.9.1.1 Culvert Replacement Applications

Improved hydrologic methods or changed watershed conditions are factors that can cause an older, existing culvert to be inadequate. A culvert analysis that relies on findings that ignore any available temporary storage may be misleading. A flood routing analysis may show that what was thought to be an inadequate existing culvert is, in fact, adequate.

Often existing culverts require replacement due to corrosion or abrasion. This can be very costly, particularly where a high fill is involved. A less costly alternative is to place a smaller culvert inside the existing culvert. A flood routing analysis may, where there is sufficient storage, demonstrate that this is acceptable in that no increase in flood hazard results.

9.9.1.2 Environmental

With culvert flood routing, a more realistic assessment can be made where environmental concerns are important. The temporary time and extent of upstream ponding can be estimated. This allows environmental specialists to assess whether such ponding is beneficial or harmful to localized environmental features (e.g., fisheries, beaver ponds, wetlands, uplands).

9.9.1.3 Flood Hazards

Potential flood hazards increase upstream wherever a culvert increases the natural flood stage. Some of these hazards can conservatively be assessed without flood routing. However, some damages associated with culvert backwater are time dependent and thus require an estimate of depth versus duration of inundation. Some vegetation and commercial crops can tolerate longer periods of inundation than others and to greater depths. Such considerations become even more important when litigation is involved.

9.9.1.4 Sediment

Complex culvert sediment deposition (“silting”) solutions require a sediment routing analysis. This practice requires a time-flood discharge relationship or hydrograph. This flood hydrograph must be coupled to a flood discharge-sediment discharge relationship to route the sediment through the culvert site.

9.9.1.5 Limitations

There are situations where culvert sizes and velocities obtained through flood routing will not differ significantly from those obtained by designing to the selected peak discharge and ignoring any temporary upstream storage. This occurs where:

- there is no significant temporary pond storage available (as in deep incised channels),
- the culvert must pass the design discharge with no increase in the natural channel's flood stage, and
- runoff hydrographs last for long periods of time such as with snowmelt runoff ((or irrigation flows)).

9.9.2 Routing Equations

In addition to the previous Design Equations (Section 9.5), the following routing equations shall be used. The basic flood routing equation is:

$$I - O = \Delta S / \Delta t, \text{ or} \quad (9.14)$$

$$2S_1 / \Delta t - O_1 + I_1 + I_2 = 2S_2 / \Delta t + O_2 \quad (9.15)$$

For a finite interval of time, Δt , Equation 9.14 can be expressed by:

$$\Delta S = Q_i \Delta t - Q_o \Delta t \quad (9.16)$$

From these equations:

$$(I_1 + I_2) / 2 = \Delta S / \Delta t + O_1 / 2 + O_2 / 2 \quad (9.17)$$

where: $\Delta S = S_2 - S_1$

S_1 = storage volume in the temporary pond at the beginning of the incremental time period Δt , ft^3

S_2 = storage volume in the temporary pond at the end of the incremental time period Δt , ft^3

Δt = incremental routing time interval selected to subdivide hydrograph into finite time elements, s

I = average hydrograph inflow to the temporary pond during incremental time period Δt , ft^3/s

I_1 = instantaneous inflow to the temporary pond at the beginning of the incremental time period Δt , ft^3/s

I_2 = instantaneous inflow at the end of the time period Δt , ft^3/s

O = average outflow from the temporary pond during incremental time period Δt , ft^3/s

O_1 = instantaneous outflow at the beginning of the time period Δt , ft^3/s

O_2 = instantaneous outflow at the end of the time period Δt , ft^3/s

9.9.3 Design Procedure

The design procedure for flood routing through a culvert is the same as for reservoir routing. The site data and roadway geometry are obtained (Data Collection Chapter) and the hydrology analysis completed to include estimating a hydrograph (Hydrology Chapter). Once this essential information is available, the culvert can be designed.

Flood routing through a culvert can be time consuming. It is recommended that the HYDRAIN (7) system be used because it contains software that very quickly routes floods through a culvert to evaluate an existing culvert (review) or to select a culvert size that satisfies given criteria (design).

However, the designer should be familiar with the culvert flood-routing design process. This familiarization is necessary to:

- recognize and test suspected software malfunctions,
- circumvent any software limitations,
- flood route manually where the software is limited, and
- understand and credibly discuss culvert flood routing.

The Design Steps are outlined below and a Design Example provided. The Example manually illustrates how flood routing for a selected time interval will result in the flood-routing findings from a computer analysis obtained using the HYDRAIN system. This Example demonstrates how to manually accomplish a culvert flood-routing analysis. For brevity, it does not contain individual computations for every time increment.

9.9.3.1 Trial and Error

A multiple, trial-and-error procedure is required for culvert flood routing. In general:

- a trial culvert(s) is selected;
- a trial culvert discharge (outflow) for a particular inflow hydrograph time element is selected;
- flood-routing computations are made with successive trial discharges until the flood-routing equation is satisfied;
- the hydraulic findings are compared to the selected site criteria; and
- if the selected site criteria are satisfied, then a trial discharge for the next time increment is selected and this procedure is repeated; if not, a new trial culvert is selected and the entire procedure is repeated.

Note: The analysis is simplified if a multiple iteration is not necessary, if the culvert performance is in inlet control over the range of appropriate discharges or if the tailwater is below critical depth for outlet control over the range of discharges.

9.9.3.2 Design Steps

The design Steps are as follows:

- Step 1 HYDROGRAPH. Plot the selected design and review hydrograph as computed using the practices from the Hydrology Chapter. Select a time interval, Δt , for use in the flood routing procedure and subdivide the hydrograph into these increments.
- Step 2 DISCHARGE CURVE. Using the practices in the Channel Chapter, compute and plot a stage-discharge curve for the downstream channel.

- Step 3 CULVERT PERFORMANCE CURVE. Compute and plot a culvert performance curve (headwater versus discharge) for the trial culvert(s). Where overtopping occurs, it is necessary that the upper end of this performance curve be adjusted to reflect this additional discharge. This additional discharge is computed using the weir equation as adjusted to reflect a roadway embankment and any downstream effects where a low roadway fill is involved. This performance curve is the spillway discharge curve commonly used in reservoir routing.
- Step 4 STAGE-STORAGE CURVE. Compute and plot a stage-storage curve for the temporary upstream pond.
- Step 5 INITIAL ROUTING STEP. Start with the first inflow hydrograph time increment:
- Determine the average hydrograph inflow and the volume discharge corresponding to the first selected time increment.
 - Recognizing that, with an increasing headwater, the temporary pond storage will generally reduce this inflow, select a trial outflow (from the culvert) discharge that is less than the inflow discharge.
 - With this smaller outflow discharge, estimate the headwater from the trial culvert(s) performance curve.
 - Use this headwater to estimate the storage volume corresponding to this headwater from the upstream stage-storage curve.
 - Compute the outflow volume corresponding to this selected outflow discharge and the previously selected time increment.
 - Subtract this volume from the foregoing average inflow volume; this is the volume that would have to go into temporary upstream pond storage.
 - Compare this volume with the volume corresponding to the previously estimated headwater. If they are the same (or nearly so), proceed to the next Step; if not, repeat this Step using a different trial outflow discharge.
- Step 6a INCREASING HW. The procedure for subsequent routing Steps where the headwater is increasing is similar to the Initial Routing Step. The difference is in how storage is handled:
- Determine the average hydrograph inflow and volume discharge corresponding to the next selected time increment.
 - Recognizing that, with an increasing headwater, the temporary pond storage will generally reduce this inflow, select a trial outflow (from the culvert) discharge that is less than the inflow discharge.
 - With this smaller outflow discharge, estimate the headwater from the trial culvert(s) performance curve.

- Use this headwater to estimate the storage volume corresponding to this headwater from the upstream stage-storage curve.
- Compute the outflow volume corresponding to this selected outflow discharge and the previously selected time increment.
- Subtract this volume from the foregoing average inflow volume; this is the volume that would have to go into temporary upstream storage.
- Add this volume to the volume already in storage.
- Compare this total volume with the volume corresponding to the previously estimated headwater. If they are the same (or nearly so), proceed to the next Step. If not, repeat this Step using a different trial outflow discharge.

Step 6b **DECREASING HW.** The procedure is similar to the subsequent Routing Steps for an Increasing Headwater. The difference is (1) the selected trial culvert outflow discharge will be greater than the average inflow hydrograph discharge, and (2) the outflow volume is greater than the inflow volume so that the temporary pond storage volume will be decreasing:

- Determine the average hydrograph inflow and volume discharge corresponding to the next selected time increment.
- Recognizing that, with a decreasing headwater, the temporary pond storage will be decreasing, select a trial outflow (from the culvert) discharge that is larger than the inflow discharge.
- With this larger outflow discharge, estimate the headwater from the trial culvert(s) performance curve.
- Use this headwater to estimate the storage volume corresponding to this headwater from the upstream stage-storage curve.
- Compute the outflow volume corresponding to this selected outflow discharge and the previously selected time increment.
- Subtract this volume from the foregoing average inflow volume; this is the volume that would have to go into temporary upstream pond storage.
- Subtract this volume from the volume already in storage.
- Compare this total volume with the volume corresponding to the previously estimated headwater, If they are the same (or nearly so), proceed to the next Step; if not, repeat this Step using a different trial outflow discharge.

Step 7 **CRITERIA CHECK.** Following (or during) the foregoing routing Steps, compare the resulting headwater and outlet velocity, and temporary pond size and duration, with the corresponding criteria selected for the site. Should there be a violation of these criteria, return to Step 1 and select a larger trial culvert; a smaller trial culvert would be selected if there appeared to be a significant over design.

9.9.4 Design Example

This example demonstrates the Design Procedure where there is no road overtopping. From the drainage survey, the site has the downstream channel characteristics of Figure 9-17. These characteristics are listed in Table 9-2. Channel slope = 0.0094 m/m.

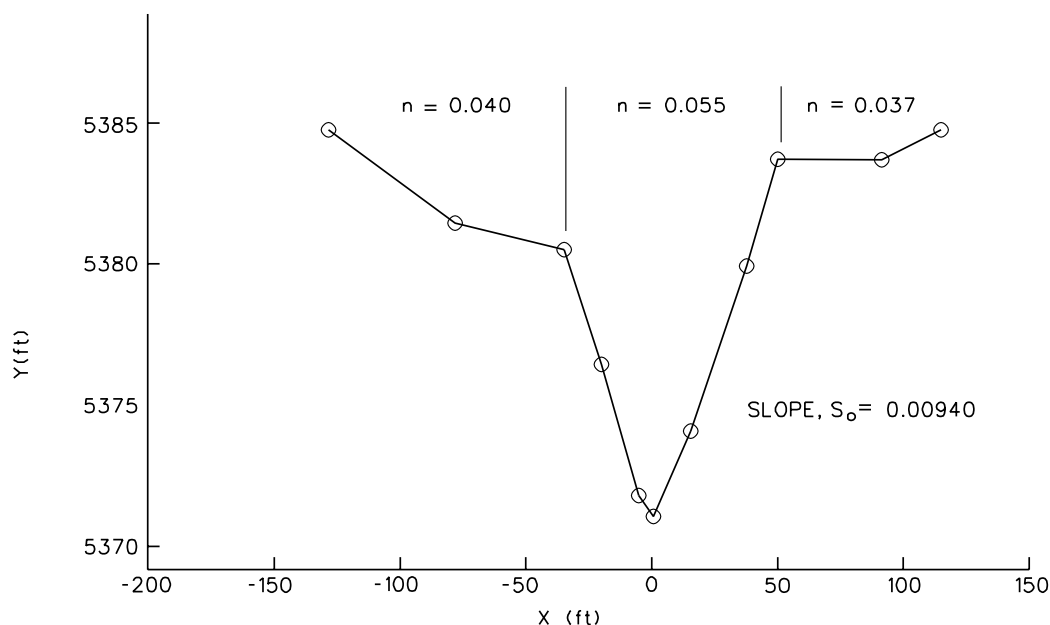


FIGURE 9-17 — Downstream Channel

TABLE 9-2 — Downstream Channel Characteristics

X Coordinate (ft)	Y Coordinate (ft)	Channel Friction (Manning's Number)
-125	5385.4	0.040
-77	5382.1	0.040
-35	5381.1	0.040
-20	5376.5	0.055
-5	5372.4	0.055
0	5371.1	0.055
15	5374.8	0.055
37	5380.5	0.055
50	5384.4	0.055
90	5384.6	0.055
113	5385.4	0.037

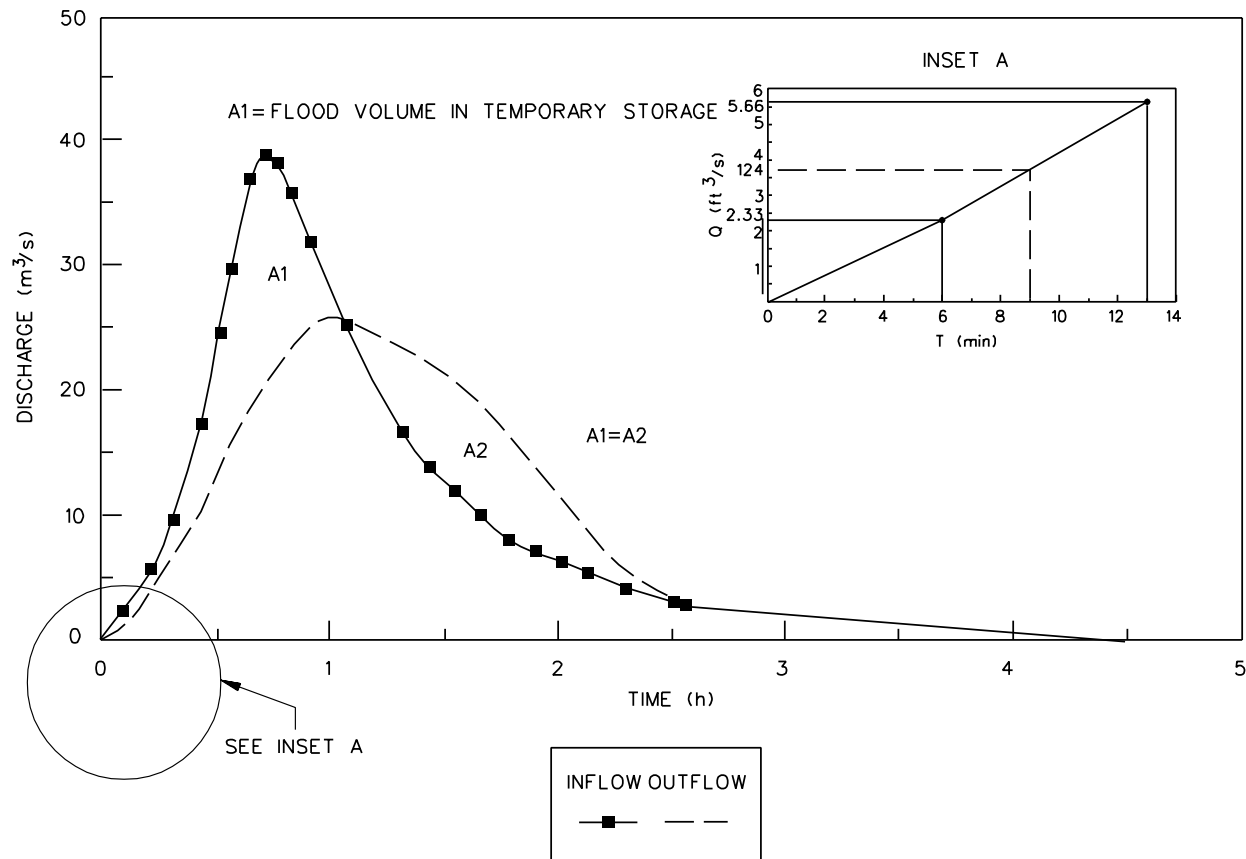


FIGURE 9-18 — Inflow Hydrograph

- Step 1 **HYDROGRAPH.** A hydrologic analysis was made that resulted in an estimated peak discharge of 1390 ft^3/s and the expected inflow hydrograph of Figure 9-18 that has a volume of approximately 107 ac•ft.
- Step 2 **DISCHARGE CURVE.** A channel analysis was made that resulted in the downstream stage-discharge (tailwater) relationship shown in Figure 9-19. These findings are also listed in Table 9-3.
- Step 3 **CULVERT PERFORMANCE CURVE.** Using the stage-discharge relationships of Figure 9-19, compute a performance curve for the selected trial culvert geometry. This rating curve can be developed in Step 3 using either the nomograph or microcomputer procedures described in Section 9.5. *Note: Flood-routing (storage) considerations are not involved in devising this performance curve. In flood-routing vernacular, this would be referred to as the "spillway rating curve."*

For a trial culvert size, select a 102-in structural plate pipe (SPP). The culvert is approximately 109 ft long and proposed to be placed on a 1% slope. Data for a performance curve was computed and is shown in Table 9-4 and plotted on Figure 9-20.

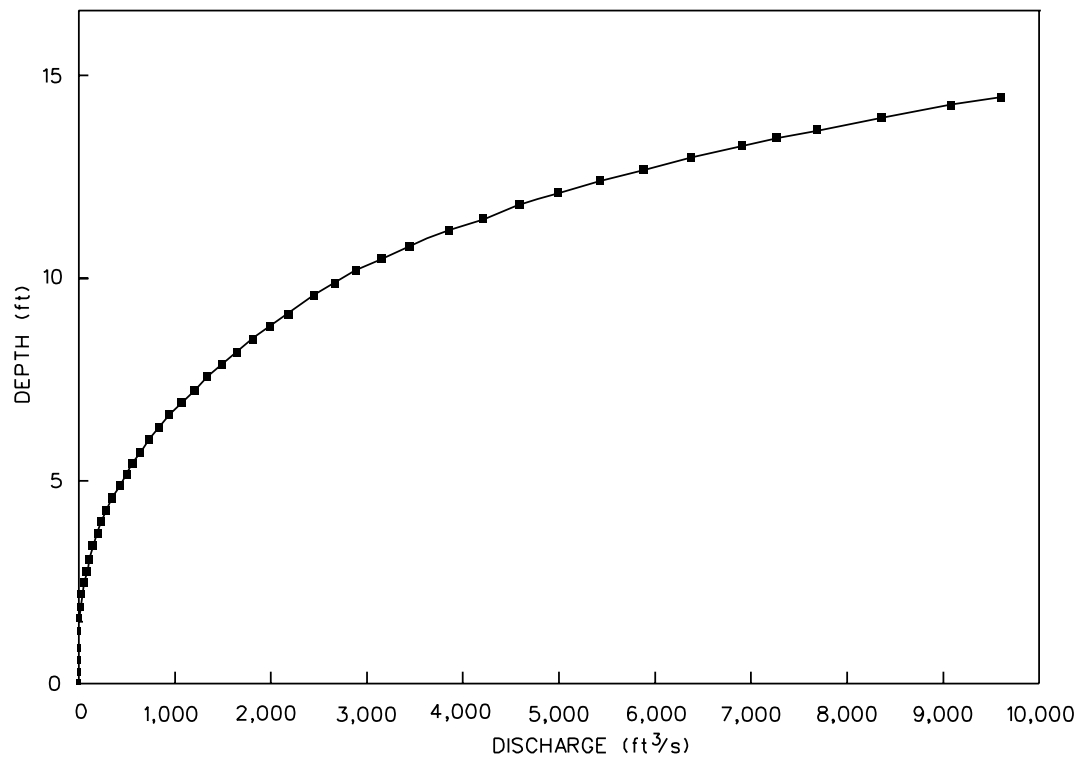
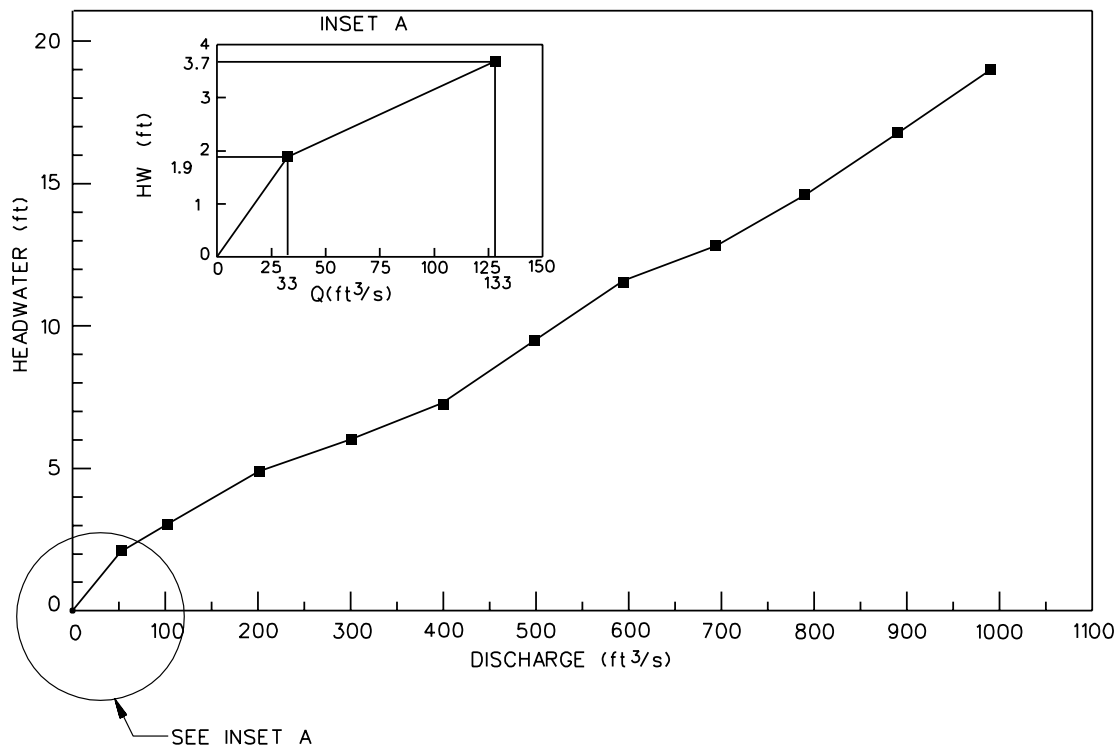
**FIGURE 9-19 — Stage-Discharge For Tailwater****FIGURE 9-20 — Culvert Performance Curve (102-in SPP)**

TABLE 9-3 — Downstream Channel Analysis Findings

Culvert Design System (Hydrain) Channel Slope = 0.00940 ft/ft				
Elevation (ft)	Depth (ft)	Discharge (ft ³ /s)	Velocity (ft/s)	Max. Velocity (ft/s)
5371.10	0.00	0.00	0.00	0.00
5371.40	0.30	0.26	0.72	0.72
5371.70	0.60	1.63	1.15	1.32
5372.00	0.90	4.81	1.51	1.81
5372.40	1.30	12.85	1.93	2.40
5372.70	1.60	22.38	2.22	2.79
5373.00	1.90	35.36	2.49	3.15
5373.30	2.20	52.20	2.74	3.50
5373.60	2.50	73.29	2.99	3.83
5373.90	2.80	99.00	3.22	4.14
5374.20	3.10	129.69	3.45	4.45
5374.50	3.40	165.71	3.67	4.74
5374.80	3.70	207.60	3.88	5.03
5375.10	4.00	255.53	4.09	5.31
5375.40	4.30	309.71	4.29	5.59
5375.70	4.60	370.44	4.49	5.85
5376.00	4.90	438.00	4.69	6.11
5376.30	5.20	512.68	4.88	6.37
5376.50	5.40	566.92	5.00	6.54
5376.80	5.70	655.07	5.19	6.79
5377.10	6.00	750.94	5.38	7.04
5377.40	6.30	854.78	5.57	7.28
5377.70	6.60	966.83	5.74	7.52
5378.00	6.90	1087.32	5.92	7.75
5378.30	7.20	1216.49	6.09	7.98
5378.60	7.50	1354.57	6.26	8.20
5378.90	7.80	1501.80	6.43	8.42
5379.20	8.10	1658.39	6.60	8.64
5379.50	8.40	1824.57	6.76	8.86
5379.80	8.70	2000.00	6.92	9.07

**TABLE 9-3 — Downstream Channel Analysis Findings
(Continued)**

Culvert Design System (Hydrain) Channel Slope = 0.00940 ft/ft				
Elevation (ft)	Depth (ft)	Discharge (ft ³ /s)	Velocity (ft/s)	Max. Velocity (ft/s)
5380.10	9.00	2186.57	7.08	9.28
5380.50	9.40	2452.35	7.29	9.55
5380.80	9.70	2666.01	7.45	9.77
5381.10	10.00	2890.57	7.61	9.98
5381.40	10.30	3152.84	7.80	10.27
5381.70	10.60	3433.68	7.94	10.55
5382.10	11.00	3846.45	8.07	10.90
5382.40	11.30	4194.03	8.18	11.17
5382.70	11.60	4569.18	8.29	11.42
5383.00	11.90	4971.92	8.41	11.67
5383.30	12.20	5402.58	8.54	11.90
5383.60	12.50	5861.65	8.68	12.12
5383.90	12.80	6349.74	8.82	12.34
5384.20	13.10	6867.48	8.96	12.55
5384.40	13.30	7231.84	9.06	12.69
5384.60	13.50	7643.91	9.15	12.89
5384.90	13.80	8314.45	9.25	13.16
5385.20	14.10	9043.24	9.38	13.42
5385.40	14.30	9561.59	9.45	13.58

TABLE 9-4 — 102-in SPP Culvert Performance Data

Discharge (ft ³ /s)	Headwater (ft)
0	0
50	2.1
100	3.1
200	5.0
300	6.2
400	7.5
500	9.8
600	12.0
700	13.3
800	15.2
900	17.5
1000	19.8

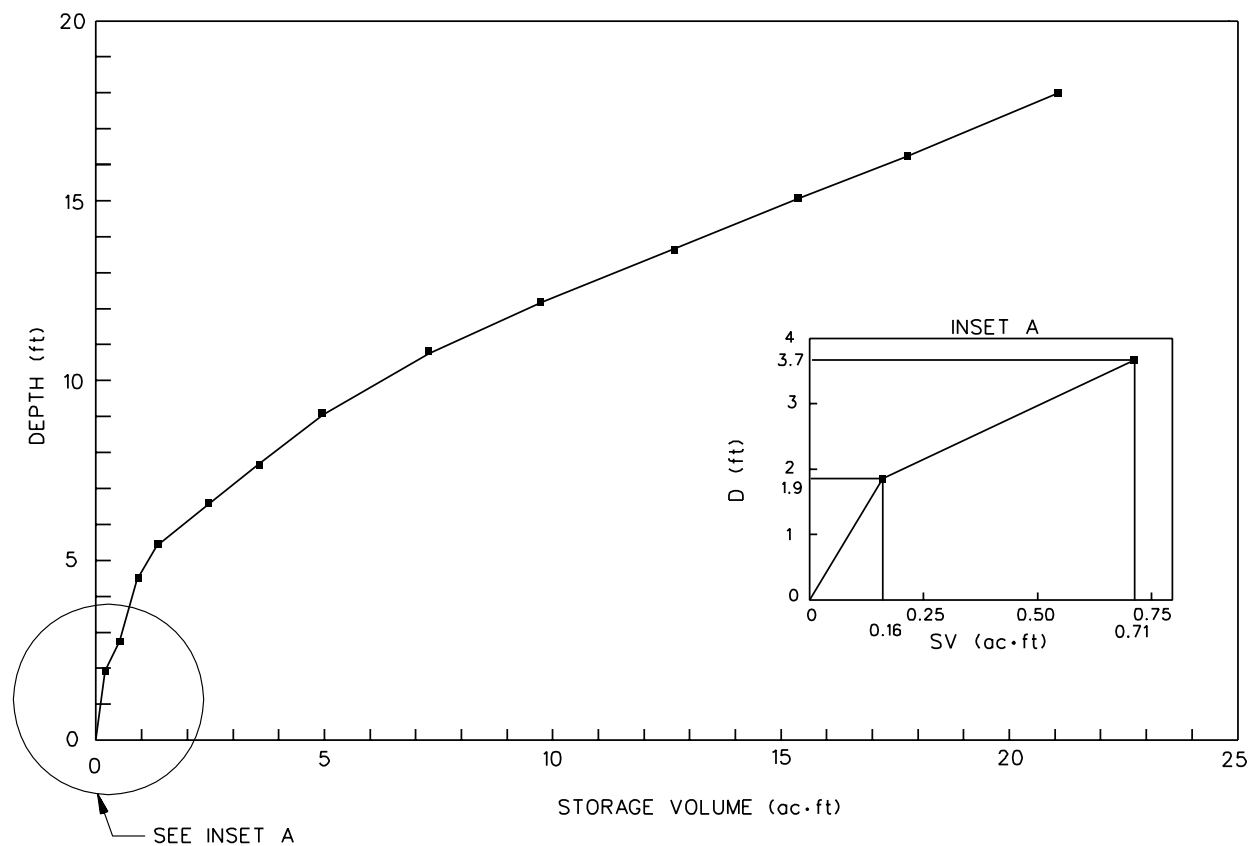


FIGURE 9-21 — Stage-Storage Relationship

TABLE 9-5 — Upstream Stage-Storage Relationship

Headwater (ft)	Storage (ac•ft)	Pond Area (ac)
0	0	0
1.90	0.16	0.10
2.69	0.48	0.20
4.49	0.89	0.40
5.51	1.29	0.50
6.69	2.42	0.70
7.81	3.47	0.90
9.29	4.84	1.20
10.99	7.10	1.80
12.40	9.53	3.70
13.91	12.35	6.50
15.39	15.02	9.20
16.60	17.36	11.50
18.50	20.59	14.80

- Step 4 **STAGE-STORAGE CURVE.** An analysis of the upstream topography resulted in the stage-storage curve of Figure 9-21. These findings are listed in Table 9-5. These volumes are those above the culvert's inlet invert flow line. Also shown in Table 9-5 is the corresponding, temporary pond surface area for various pond depths.
- Step 5 **FLOOD-ROUTING.** Having determined all the important site-specific relationships, the next step is to do the flood routing through the culvert. This is a trial-and-error process.

In this Example, Table 9-6 reflects the flood routing analysis completed using the HYDRAIN software. However, a similar table would be forthcoming if the flood routing were done manually. The remainder of this Example will demonstrate how to manually reach some of the findings in Table 9-6. Manual computations may result in findings that differ slightly from those in Table 9-6. This is because the computer is more precise in that it uses smaller time increments than those shown in Table 9-6.

9.9.4.1 Initial Time Increment

The following illustrates how the initial (first) line of data in Table 9-6 was computed. In the computer analysis, this was not the initial time increment because there were actually several other intermediate increments. This accounts for the slight discrepancies noted below:

- Arbitrarily select a time increment of say 6 min, which corresponds to an inflow discharge of 82 ft³/s from Figure 9-18.
- The average inflow volume, *I*, corresponding to 82 ft³/s would be $[(0 + 82 \text{ ft}^3/\text{s})/2](6 \text{ min})(60 \text{ s/min})/43,560 \text{ ft}^2/\text{ac}$ or 0.34 ac•ft. Because this is the initial increment, there was no prior inflow, so the total inflow at the end of 6 min is 0 + 0.34 or 0.34 ac•ft. The computer analysis of Table 9-6 shows 0.8 ac•ft.
- Select a trial outflow discharge of say 33 ft³/s. The average trial outflow volume, *O*, would be $[(0 + 33 \text{ ft}^3/\text{s})/2](6 \text{ min})(60 \text{ s/min})/43,560 \text{ ft}^2/\text{ac}$ or 0.14 ac•ft. Because this is the initial increment, there was no prior outflow, so the total outflow at the end of 6 minutes is 0 + 0.14 or 0.14 ac•ft. The truncated computer analysis of Table 9-6 shows 0.0 ac•ft for a successful trial discharge of 33 ft³/s.
- From Figure 9-20, the headwater corresponding to the trial outflow discharge of 33 ft³/s would be 1.90 ft, which agrees closely with the 1.97 ft from the computer analysis of Table 9-6.
- For a headwater of 1.90 ft, the total upstream storage volume, ΔS , would be 0.16 ac•ft as determined from Figure 9-21. This volume must agree later with the total volume estimated to have been placed into storage.
- The amount of runoff volume going into storage, ΔS , is $\Delta S = I - O = 0.34 - 0.16$ or 0.18 ac•ft.
- The total volume in storage is the sum of the amount in storage from the previous time increment plus ΔS . Because there was no previous time increment, the total amount in storage would be $0 + 0.18 = 0.18 \text{ ac}\bullet\text{ft}$, which again agrees with the truncated 0.0 ac•ft from the computer analysis of Table 9-6.

- The total volume in storage, 0.18 ac•ft, must equal the previously computed total upstream storage volume of 0.16 ac•ft corresponding to the headwater of 1.90 ft necessary to discharge the trial 33 ft³/s through the culvert. Because the values are very similar, consider the trial outflow of 33 ft³/s as acceptable. The computer analysis of Table 9-6 was also able to balance the storage equation with an average outflow of 33 ft³/s.
- Plot the outflow discharge of 33 ft³/s on Figure 9-18 and proceed to the first intermediate time increment.

9.9.4.2 Intermediate Time Increment

The following illustrates how the next intermediate line of data in Table 9-6 was completed. This is typical for any intermediate time increment where the headwater is increasing:

- Arbitrarily select a time increment of say 7 min, which corresponds to an inflow discharge of 200 ft³/s from Figure 9-18, at (6 + 7) or 13 min total.
- The average inflow volume, I , corresponding to 200 ft³/s for this time increment would be $[(82 + 200)/2](7 \text{ min}) (60 \text{ s/min})/43,560 \text{ ft}^2/\text{ac}$ or 1.36 ac•ft. The total inflow prior to this increment was 0.34 ac•ft, which results in a total inflow at the end of 13 min of $0.34 + 1.36 = 1.70 \text{ ac•ft}$, which essentially agrees with the 1.6 ac•ft of Table 9-6.
- Select a trial outflow discharge of say 133 ft³/s. The average trial outflow volume would be $[(33 + 133)/2](7 \text{ min}) (60 \text{ s/min})/43,560 \text{ ft}^2/\text{ac}$ or 0.80 ac•ft. The total outflow prior to this increment was 0.14 ac•ft, which results in a total outflow at the end of 13 min of $0.14 + 0.80 = 0.94 \text{ ac•ft}$, which essentially agrees with the 0.8 ac•ft of Table 9-6.
- From Figure 9-20, the headwater corresponding to the trial outflow discharge of 133 ft³/s would be 3.7 ft, which agrees closely with the 4.3 ft from the computer analysis of Table 9-6.
- For a headwater of 3.7 ft, the total upstream storage volume, ΔS , would be 0.74 ac•ft as determined from Figure 9-21. This volume must agree later with the total volume estimated to have been placed in storage.
- The amount of runoff volume going into storage, ΔS , is $\Delta S = I - O = 1.36 - 0.80 = 0.56 \text{ ac•ft}$.

Note: If the headwater were decreasing, then from the previous time increment the total volume in storage would also be decreasing. When this occurs, the volume going into storage, ΔS , will be a negative value because outflow volume, O , is greater than the inflow volume, I .

- The total volume in storage is the sum of the amount in storage from the previous time increment plus ΔS . The amount in storage from the previous time increment was 0.18 ac•ft. Therefore the total amount in storage at the end of this time increment would be $0.18 + 0.56$ or 0.74 ac•ft.

Note: If the headwater is decreasing, then the volume, ΔS , going into storage from the previous computation will be negative. This means that the volume, ΔS , is to be subtracted from the previous volume in storage rather than added because this volume is decreasing.

- The total volume in storage, $0.74 \text{ ac}\cdot\text{ft}$, must equal the previously computed upstream storage volume of $0.73 \text{ ac}\cdot\text{ft}$, which corresponds to the headwater of 3.7 ft necessary to discharge the trial $133 \text{ ft}^3/\text{s}$ through the culvert. Because this is the case, consider the trial outflow of $133 \text{ ft}^3/\text{s}$ as acceptable. This finding agrees with the computer analysis of Table 9-6.
- Plot the outflow discharge of $133 \text{ ft}^3/\text{s}$ on Figure 9-18 and proceed to the next time increment.

9.10 TAPERED INLETS

9.10.1 General

A tapered inlet is a flared culvert inlet with an enlarged face section and a hydraulically efficient throat section. A tapered inlet may have a depression, or FALL, incorporated into the inlet structure or located upstream of the inlet. The depression is used to exert more head on the throat section for a given headwater elevation. Therefore, tapered inlets improve culvert performance by providing a more efficient control section (the throat). Tapered inlets are not recommended for use on culverts flowing in outlet control because the simple beveled edge is of equal benefit.

- Design criteria and methods have been developed for two basic tapered inlet designs: the side-tapered inlet and the slope-tapered inlet.
- Tapered inlet design charts are available for rectangular-box culverts and circular-pipe culverts.

9.10.2 Side-Tapered Inlets

The side-tapered inlet has an enlarged face section with the transition to the culvert barrel accomplished by tapering the side walls (Figure 9-22). The face section is approximately the same height as the barrel height, and the inlet floor is an extension of the barrel floor. The inlet roof may slope upward slightly, provided that the face height does not exceed the barrel height by more than 10% (1.1D). The intersection of the tapered sidewalls and the barrel is defined as the throat section.

There are two possible control sections — the face and the throat. HW_f , shown in Figure 9-22, is the headwater depth measured from the face section invert, and HW_t is the headwater depth measured from the throat section invert. The throat of a side-tapered inlet is a very efficient control section. The flow contraction is nearly eliminated at the throat. In addition, the throat is always slightly lower than the face so that more head is exerted on the throat for a given headwater elevation.

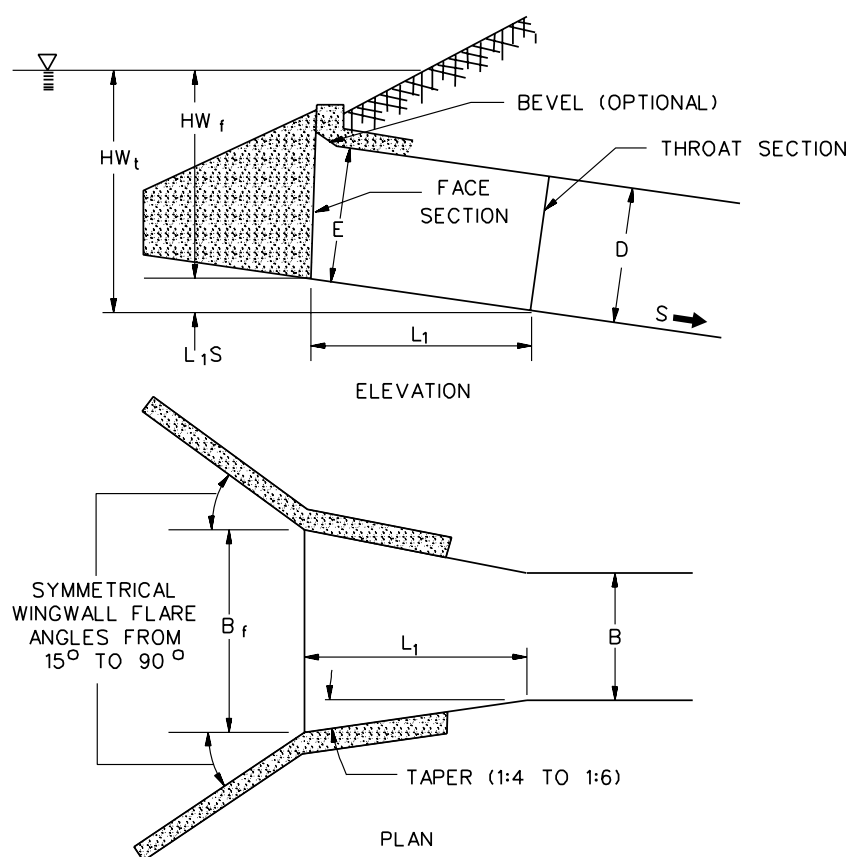


FIGURE 9-22 — Side-Tapered Inlet

The beneficial effect of depressing the throat section below the streambed can be increased by installing a depression upstream of the side-tapered inlet. Figure 9-23 depicts a side-tapered inlet with the depression contained between wingwalls. For this type of depression, the floor of the barrel should extend upstream from the face a minimum distance of $D/2$ before sloping upward more steeply. The length of the resultant upstream crest where the slope of the depression meets the streambed should be checked to assure that the crest will not control the flow at the design flow and headwater. If the crest length is too short, the crest may act as a weir-control section; the barrel is defined as the throat section.

9.10.3 Slope-Tapered Inlets

The slope-tapered inlet, like the side-tapered inlet, has an enlarged face section with tapered sidewalls meeting the culvert barrel walls at the throat section (Figure 9-24). In addition, a vertical FALL is incorporated into the inlet between the face and throat sections. This FALL concentrates more head on the throat section. At the location where the steeper slope of the inlet intersects the flatter slope of the barrel, a third section, designated the bend section, is formed.

A slope-tapered inlet has three possible control sections — the face, the bend and the throat. Of these, only the dimensions of the face and the throat section are determined by the design procedures of this *Manual*. The size of the bend section is established by locating it a minimum distance upstream from the throat so that it will not control the flow.

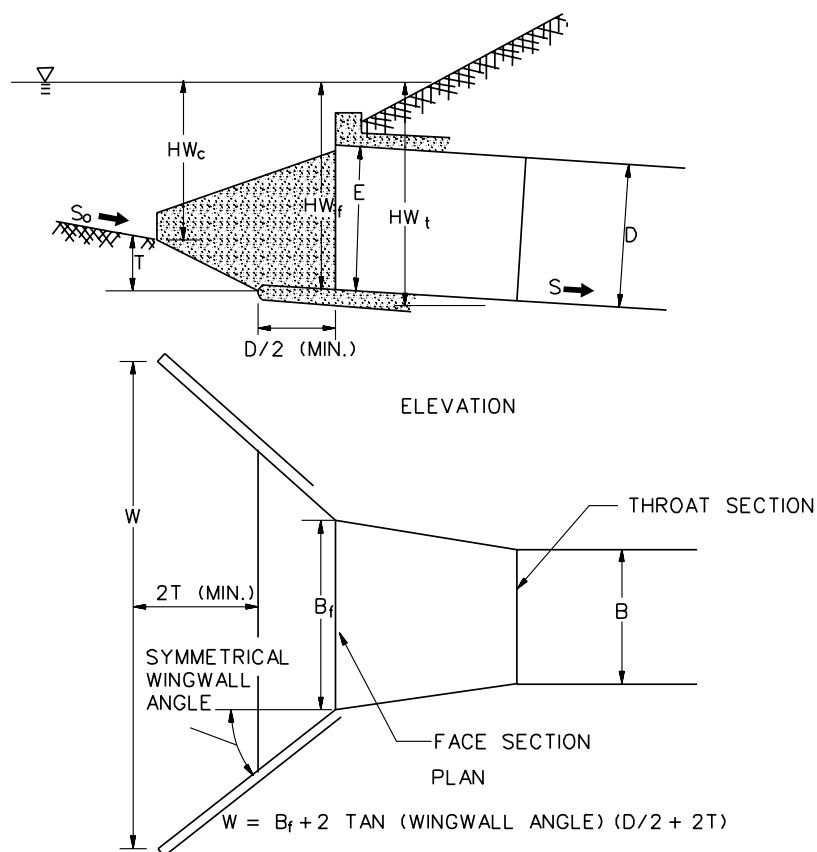


FIGURE 9-23 — Side-Tapered Inlet with Upstream Depression Contained Between Wingwalls

The slope-tapered inlet combines an efficient throat section with additional head on the throat. The face section does not benefit from the FALL between the face and throat; therefore, the face sections of these inlets are larger than the face sections of equivalent depressed side-tapered inlets. The required face size can be reduced by the use of bevels or other favorable edge configurations. The vertical face slope-tapered inlet design is shown in Figure 9-24.

The slope-tapered inlet is the most complex inlet improvement recommended in this *Manual*. Construction difficulties are inherent, but the benefits in increased performance can be significant. With proper design, a slope-tapered inlet passes more flow at a given headwater elevation than any other configuration. Slope-tapered inlets can be applied to both box culverts and circular-pipe culverts. For the latter application, a square-to-round transition is normally used to connect the rectangular, slope-tapered inlet to the circular pipe.

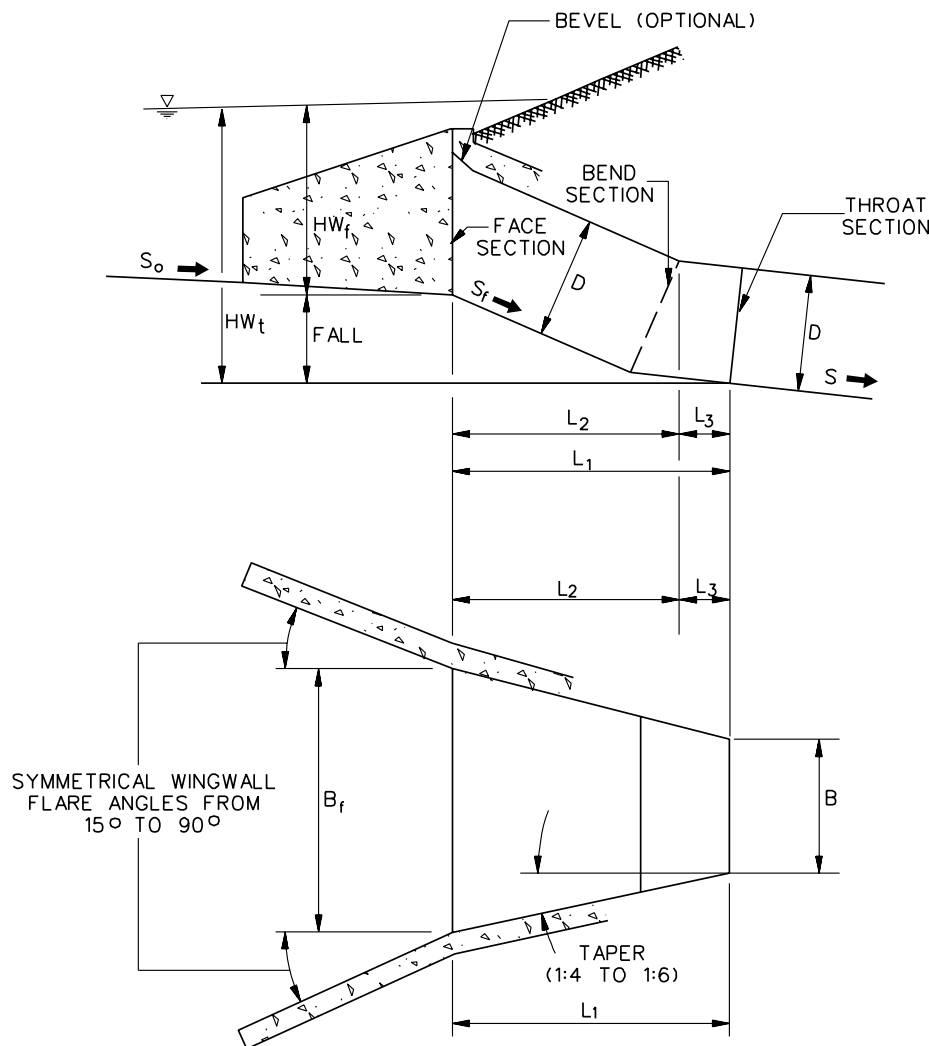


FIGURE 9-24 — Slope-Tapered Inlet with Vertical Face

9.10.4 Hydraulic Design

9.10.4.1 Inlet Control

Tapered inlets have several possible control sections including the face, the bend (for slope-tapered inlets) and the throat. In addition, a depressed side-tapered inlet has a possible control section at the crest upstream of the depression. Each of these inlet control sections has an individual performance curve. The headwater depth for each control section is referenced to the invert of the section. One method of determining the overall inlet control performance curve is to calculate performance curves for each potential control section, and then select the segment of each curve which defines the minimum overall culvert performance (Figure 9-25).

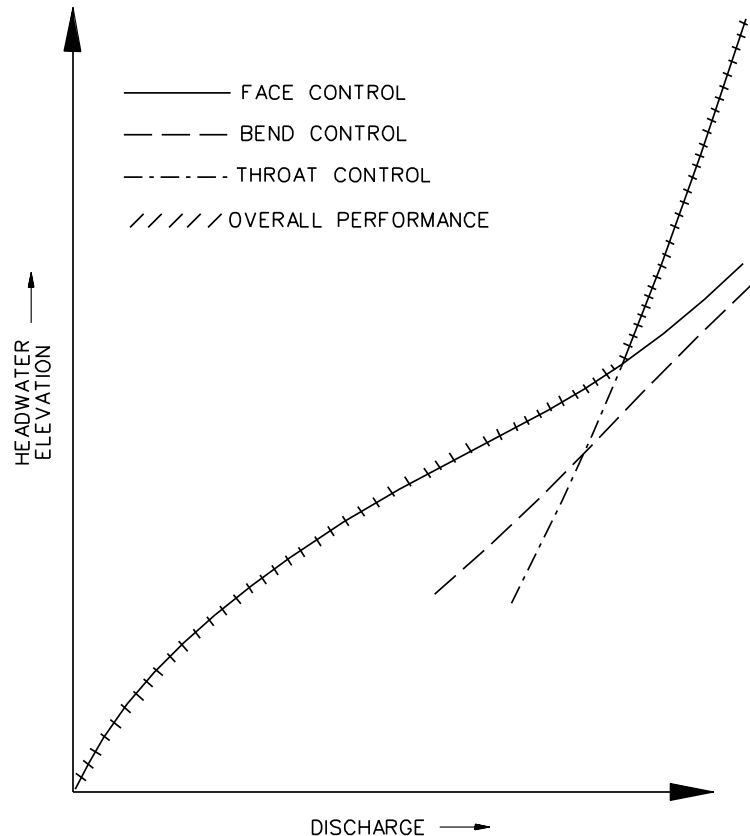


FIGURE 9-25 — Inlet Control Performance Curves (Schematic)

9.10.4.1.1 Side-Tapered Inlet

The side-tapered inlet throat should be designed to be the primary control section for the design range of flows and headwaters. Because the throat is only slightly lower than the face, it is likely that the face section will function as a weir or an orifice with downstream submergence within the design range. At lower flow rates and headwaters, the face will usually control the flow.

9.10.4.1.2 Slope-Tapered Inlet

The slope-tapered inlet throat can be the primary control section with the face section submerged or unsubmerged. If the face is submerged, the face acts as an orifice with downstream submergence. If the face is unsubmerged, the face acts as a weir, with the flow plunging into the pool formed between the face and the throat. As previously noted, the bend section will not act as the control section if the dimensional criteria of this *Manual* are followed. However, the bend will contribute to the inlet losses that are included in the inlet loss coefficient, k_E .

9.10.4.2 Outlet Control

When a culvert with a tapered inlet performs in outlet control, the hydraulics are the same as described in Section 9.5 for all culverts. The tapered inlet entrance loss coefficient (k_E) is 0.2 for both side-tapered and slope-tapered inlets. This loss coefficient includes contraction and

expansion losses at the face, increased friction losses between the face and the throat, and the minor expansion and contraction losses at the throat.

9.10.5 Design Methods

Tapered inlet design begins with the selection of the culvert barrel size, shape and material. These calculations are performed using the Culvert Design Form provided in Appendix 9.E. The design nomographs contained in Appendix 9.D are used to design the tapered inlet. The design procedure is similar to designing a culvert with other control sections (face and throat). The result will be one or more culvert designs, with and without tapered inlets, all of which meet the site design criteria. The designer must select the best design for the site under consideration.

In the design of tapered inlets, the goal is to maintain control at the efficient throat section in the design range of headwater and discharge. This is because the throat section has the same geometry as the barrel, and the barrel is the most costly part of the culvert. The inlet face is then sized large enough to pass the design flow without acting as a control section in the design discharge range. Some slight oversizing of the face is beneficial because the cost of constructing the tapered inlet is usually minor compared with the cost of the barrel.

Performance Curves

Performance curves are of utmost importance in understanding the operation of a culvert with a tapered inlet. Each potential control section (face, throat and outlet) has a performance curve, based on the assumption that the particular section controls the flow. Calculating and plotting the various performance curves results in a graph similar to Figure 9-26, containing the face control, throat control and outlet control curves. The overall culvert performance curve is represented by the hatched line. In the range of lower discharges, face control governs; in the intermediate range, throat control governs and, in the higher discharge range, outlet control governs. The crest and bend performance curves are not calculated because they do not govern in the design range.

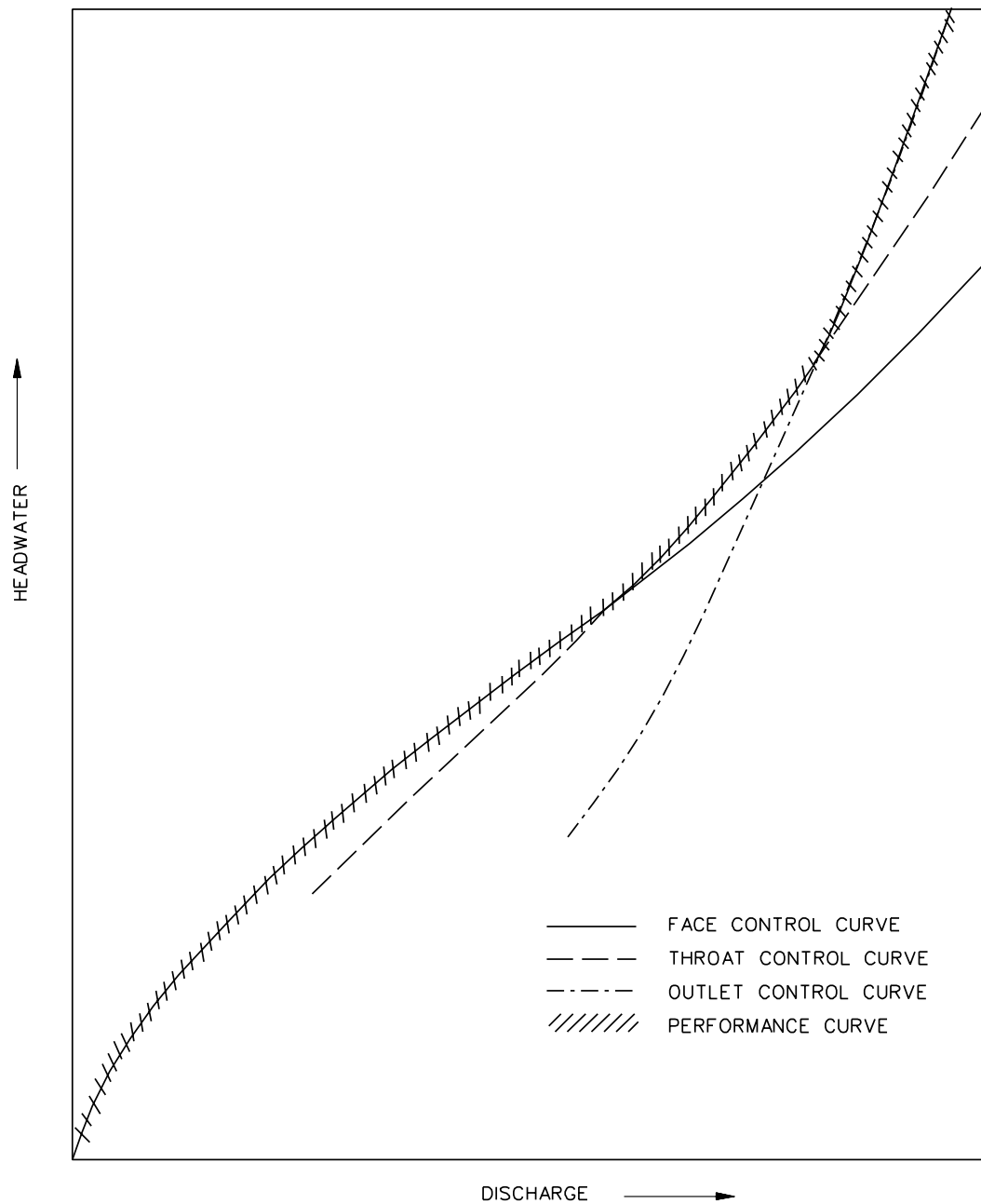


FIGURE 9-26 — Culvert Performance Curve (Schematic)

9.11 REFERENCES

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